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Space&Physics

The Universe in Glorious X-rays

A NEW TELESCOPE IS POISED
TO CREATE A MAP
OF BLACK HOLES
AND HUNDREDS OF
THOUSANDS OF STARS

Plus:

Next stop: Venus

The imminent quantum Internet

Rarely seen *Apollo 11* images

WITH COVERAGE FROM
nature

LIZ TORMES

A Whole New View

In 1800 astronomer William Herschel kicked off more than a century of discovery when he detected infrared radiation. It was the first observation of electromagnetic radiation other than visible light and the first verification that there is more in the universe than humans can see with their eyes. In fact, the human eye perceives only about 0.0035 percent of the total electromagnetic radiation in the universe. Therefore, with all our light-based telescopes, on Earth and in space, we observe a mere fraction of the radiation that fills the cosmos. To literally expand our field of view, several space missions have gathered data on the universe in x-rays, ultraviolet rays, gamma rays, and so on. Davide Castelvecchi reports on an exciting telescope launched this summer that will collect high-energy x-rays from the universe, with aims to create a 3-D map of never before seen supermassive black holes and some 700,000 stars. It gives a new definition to the term "eye-opening" (see "New Space Telescope Will Map the Universe in High-Energy X-rays").

Elsewhere in this issue, Anil Ananthaswamy covers the recent breakthroughs that are bringing a quantum Internet closer to reality (see "The Quantum Internet Is Emerging, One Experiment at a Time"). And Shannon Hall writes about the growing momentum for renewed explorations of Venus (see "Venus, Earth's Evil Twin, Beckons Space Agencies"). In our own cosmic backyard and beyond, there is so much more to see.

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Your Opinion Matters!

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On the Cover

An artist's illustration of the German-Russian telescope called SRG, which will detect millions of new supermassive black holes, and hundreds of thousands of stars.

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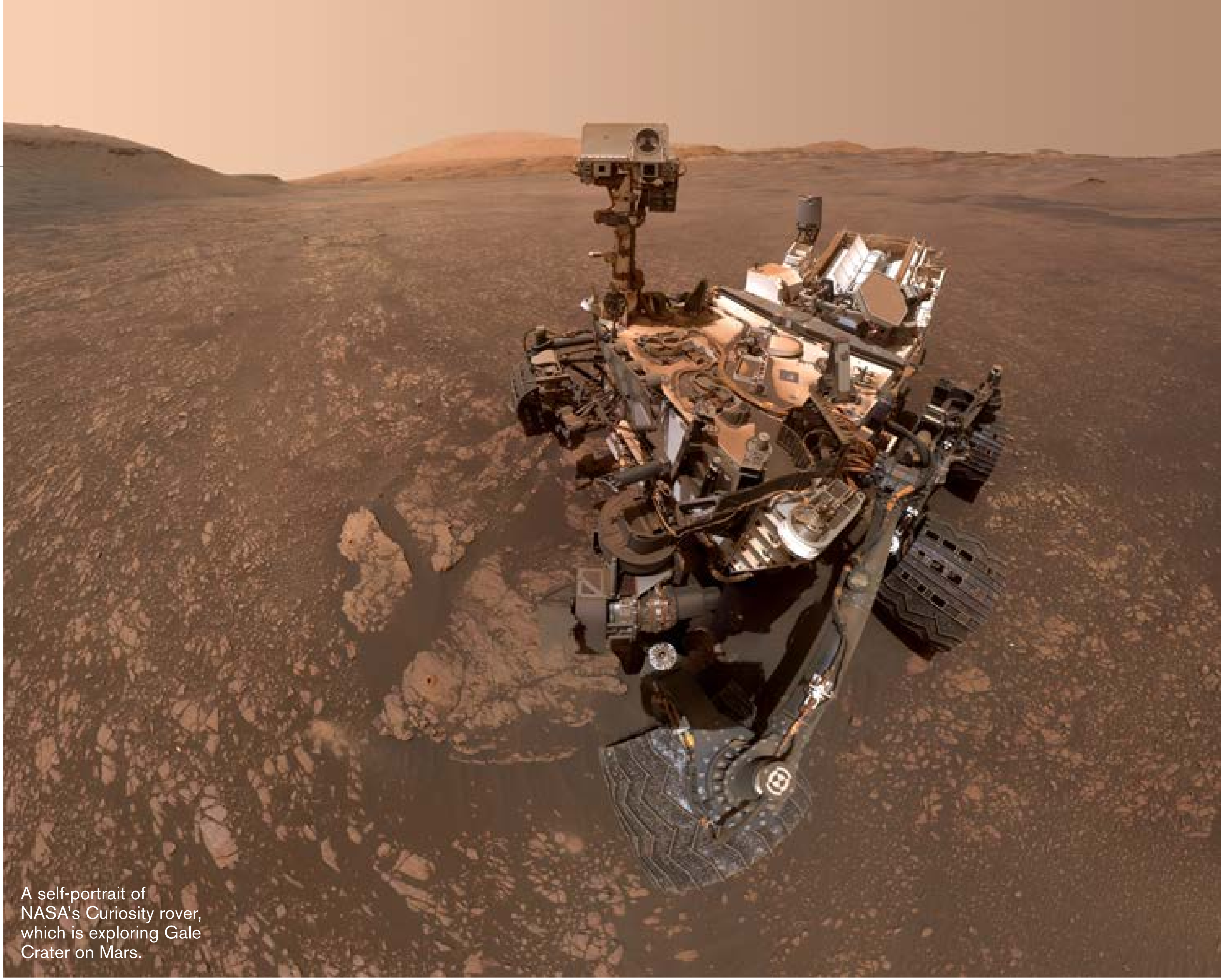

A self-portrait of NASA's Curiosity rover, which is exploring Gale Crater on Mars.

Mars Rover Detects "Excitingly Huge" Methane Spike

NASA's Curiosity rover reports the highest-ever reading of the gas at the planet's surface

NASA'S CURIOSITY ROVER has measured the highest level of methane gas ever found in the atmosphere at Mars's surface. The reading taken in June at Gale Crater—21 parts per billion—is three times greater than the previous record, which Curiosity detected back in 2013.

Planetary scientists avidly track methane on Mars because its presence could be a sign of life on the Red Planet. On Earth, most methane is produced by living things, although the gas can also come from geological sources such as chemical reactions involving rocks. Various spacecraft and telescopes have spotted methane on Mars over the past 16 years, but the gas doesn't appear in any predictable pattern—deepening the mystery of its origin.

Curiosity has measured methane many times since it landed in Gale Crater in 2012. The level is typically low, often in the parts per trillion range, and seems to rise and fall as Martian seasons change.

The latest measurement is "excitingly huge," says Oleg Korablev, a physicist at the Space Research Institute in Moscow. He runs one of the methane-sniffing instruments on the European-Russian Trace Gas

NASA/JPL-CALTECH/MSSS

Orbiter (TGO). The spacecraft launched in 2016 to solve the mystery of methane on Mars, but so far it has not spotted any of the elusive gas.

One explanation for that could be that methane is diluted or destroyed as it rises higher in the atmosphere, says Michael Mumma, a planetary scientist at NASA's Goddard Space Flight Center in Greenbelt, Md. Orbiting spacecraft such as the TGO are best suited to measure methane many kilometers above the surface.

The TGO is now searching for methane in the atmosphere high above Gale Crater. So, too, is the European Space Agency's Mars Express spacecraft, the other Mars orbiter that measures methane.

NASA is extending Curiosity's stay at its current location in the crater—a spot called Teal Ridge. Agency scientists were scheduled to run a follow-up methane experiment to see whether they can confirm high levels of methane but have not yet released their results.

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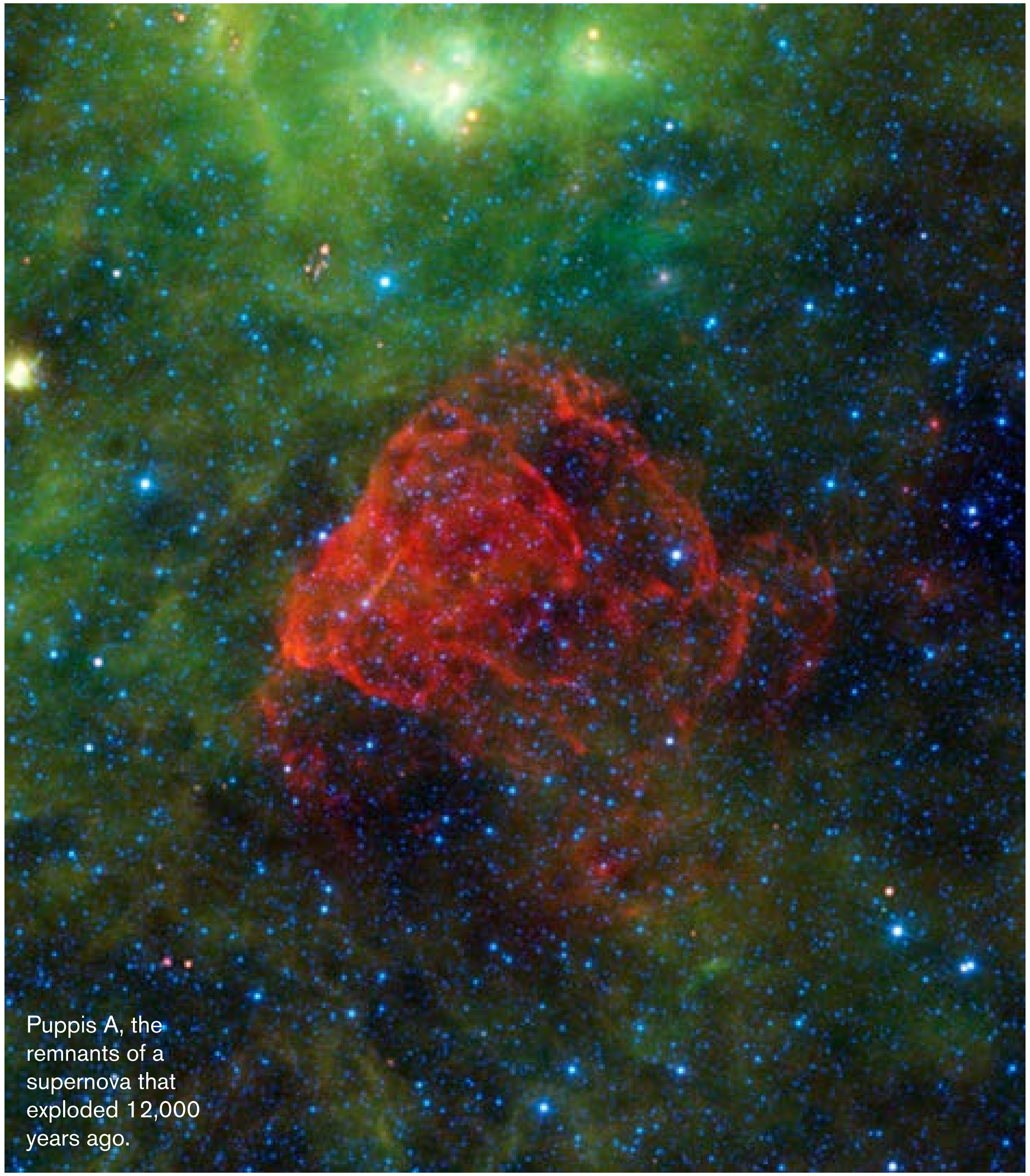
—Alexandra Witze

The Universe's First Stars Exploded in Strange Ways

A new study finds observational evidence that one of the first stars exploded in an asymmetrical blast that spread heavy elements into the cosmos


Puppis A, the remnants of a supernova that exploded 12,000 years ago.

NASA, JPL-CALTECH AND UCLA

THE EXPLOSIONS THAT blew apart the universe's first stars are shrouded in mystery. These energetic blasts are inherently difficult to re-create in computer simulations, even using modern computing power. "It's one of the hardest physics problems out there," says Alexander Ji, an astrophysicist at the Carnegie Observatories in Pasadena, Calif. Furthermore, he notes that researchers still lack an answer to a simple question: What types of stars do—and do not—explode?

Scientists often assume the first stars ended their lives as spherical supernovae. A team of researchers, however, just presented the first observational evidence that at least one of these ephemeral fireballs instead exploded aspherically, spewing its contents out unevenly in multiple directions. The explosion flung forth jets powerful enough to propel heavy elements forged in the blast into neighboring galaxies, the researchers note in a study published on May 8 in the *Astrophysical Journal*. (Ji was not involved in the study, but his former doctoral adviser is one of its authors.)

The paper is part of a major push to study the properties of the first stars, which has been a hot topic for the past decade, says Volker Bromm, an astronomer at the University of Texas at Austin, who also was not involved in the study. The idea that jets spew out of exploding stars, slinging heavy elements into neighboring galaxies and seeding the next generation of stars, is not new. Researchers have even previously theorized the occurrence of this phenomenon in the first generation of stars. Still, this study is the first to find observational evidence of it in one of these early stars.

A SPECIAL STAR

Because the first stars—short-lived giants that all died long ago—are not available to study directly, Rana Ezzeddine, an astronomer at the M.I.T. Kavli Institute for Astrophysics and Space Research and the lead author on the study, and her colleagues studied the abundances of iron and other elements found in a second-generation star called HE 1327-2326. It belongs to a rare group of about 25 to 30 ancient stars that contain very low amounts of iron. These stars arose out of elemental seeds left behind by progenitor stars from the first generation.

"Our star is very special, because it is also the brightest one" of that group, Ezzeddine says. Still, measuring its elemental abundances required the use of the Cosmic Origins Spectrograph aboard the Hubble Space Telescope—one of the most sensitive instruments available. "This is a beautiful paper," Bromm says, noting that this type of stellar sleuthing is possible only with very high-quality data.

The team members expected to find the presence of silicon, iron and phosphorus in the spectrum, but their discovery of a different element was a shocker. For the first time, they found zinc in a second-generation star, Ezzeddine says—and not just a little, but a lot. Stunned by this finding, which could signal that more heavy elements were available in the early universe than previously thought, the researchers repeated their analysis. With every check, their zinc finding persisted.

ELEMENTAL SURPRISE

This finding turned the project on its head. Researchers already knew why this star and others in its group do not contain much iron. Iron was formed in the cores of the massive first stars that were the progenitors of the metal-poor ones, Ezzeddine says. When these first stars collapsed in on themselves, much of the iron from their cores fell back into the resulting black holes, she notes. Zinc is also formed in the cores of these ancients, however, leading the team to wonder how the element escaped this black hole fate.

This oddity can be explained by an aspherical explosion of the supernova, Ezzeddine says. The resulting jets could fling the core's zinc away from a black hole while also allowing most of its iron to fall back into one. To explore this theory, the researchers ran over 10,000 computer simulations of exploding supernovae with different explosion energies and configurations. Remarkably, they discovered that none of the spherical supernovae explosions could produce the observed zinc signal. Furthermore, they found just one aspherical supernova explosion that could yield the observed zinc signal and other characteristics of HE 1327-2326.

This led them to another surprise: how powerful the asymmetrical supernova explosion could have been. Its explosiveness likely had about a nonillion times (10 with 30 zeroes after it) the power of a hydrogen bomb, the researchers estimate—that is about five to 10 times more energetic than previously thought. The study provides new evidence that the explosions of the universe's first stars may have contributed to the universe's reionization—an important milestone in the early cosmos when neutral atoms became charged—and played a critical role in the development of galaxies.

John Wise, a computational astrophysicist at the Georgia Institute of Technology who is currently studying how metals propagated from the first generation of stars to the second, says this study has already inspired him to modify his methodology for that project. "Now we have some motivation to look at aspherical supernovae," he says. Researchers do not yet know whether the likely aspherical explosion of the supernova preceding HE 1327-2326 was a rarity or a common occurrence. They still wonder whether the bulk of supernova explosions from the first generation were spherical or aspherical. So, though it appears they have approached a solution to one mystery about the first stars, numerous others abound.

—Rachel Crowell

Gravitational Waves Hint at a Black Hole Eating a Neutron Star

LIGO and Virgo observatories have spotted ripples from what could be the first-ever detection of this long-sought event

An artist's rendition of a star throwing off a glowing stream of debris as it is disrupted by a supermassive black hole.

NASA AND JPL-CALTECH

GRAVITATIONAL WAVES MAY have just delivered the first sighting of a black hole devouring a neutron star. If confirmed, it would be the first evidence of the existence of such binary systems. The news came just a day after astronomers had detected gravitational waves from a merger of two neutron stars for only the second time.

At 15:22:17 UTC on April 26, the twin detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) in the United States and the Virgo observatory in Italy reported a burst of waves of an unusual type. Astronomers are still analyzing the data and doing computer simulations to interpret them.

But they are already considering the tantalizing prospect that they have made a long-hoped-for detection that could produce a wealth of cosmic information, from precise tests of the general theory of relativity to measuring the universe's rate of expansion. Astronomers around the world are also racing to observe the phenomenon using different types of telescopes.

"I think that the classification is leaning toward a neutron star–black hole" merger, says Chad Hanna, a senior member of LIGO's data-analysis team and a physicist at Pennsylvania State University in University Park.

But the signal was not very strong, which means that it could be a fluke. "I think people should get excited about it, but they should also be aware that the significance is much lower" than in many previous events, he says. LIGO and Virgo had previously caught gravitational waves—faint ripples in the fabric of spacetime—from two types of cataclysmic event: the mergers of two black holes, and of two neutron stars. The latter are small but ultradense objects formed after the collapse of stars more massive than the sun.

The latest event, provisionally labeled #S190426c, appears to have occurred around 375 megaparsecs (1.2 billion light-years) away, the LIGO-Virgo team calculated. The researchers have drawn a sky map, showing where the gravitational waves are most likely to have originated, and sent this information out as a public alert, so that astronomers around the world could begin searching the sky for light from the event. Matching gravitational waves to other forms of radiation in this way can produce much more information about the event than either type of data can alone.

Mansi Kasliwal, an astrophysicist at the California Institute of Technology in Pasadena, leads one of several projects designed to do this type of follow-up work, called Global Relay of Observatories Watching Transients Happen (GROWTH). Her team can commandeer robotic telescopes around the world. In this case, the researchers immediately started up one in India, where it was night time when the gravitational waves arrived. "If weather cooperates, I think in less than 24 hours we should have coverage in almost the entire sky map," she says.

TWO AT ONCE

Astronomers were already working in overdrive when they spotted the potential black hole–neutron star merger. At 08:18:26 UTC on April 25, another train of waves hit the LIGO's detector in Livingston, La., and Virgo. (At the time, LIGO's second machine, in Hanford, Wash., was briefly out of commission.)

That event was a clear-cut case of two merging neutron stars, Hanna says—nearly two years after the first historic discovery of such an event was made in August 2017.

Researchers can usually make such a call because the waves reveal the masses of the objects involved; objects roughly twice as heavy as the sun are expected to be neutron stars. Based on the waves' loudness, the researchers also estimated that the collision occurred some 150 megaparsecs (500 million light-years) away, says Hanna. That was around three times farther than the 2017 merger.

Iair Arcavi, an astrophysicist at Tel Aviv University who works on the Las Cumbres Observatory, one of GROWTH's competitors, was in Baltimore, to attend a conference called Enabling Multi-Messenger Astrophysics (EMMA)—the practice of observing these events in multiple wavelengths. The alert of the April 25 event came at 5:01 A.M. "I set it up to send me a text message, and it woke me up," he says.

A storm of activity swept the meeting, with astronomers who would normally compete with each other exchanging information as they sat with their laptops around coffee tables. "We're losing our minds over here at #EMMA2019," tweeted astronomer Andy Howell.

But in this case, unlike many others, LIGO and Virgo were unable to significantly narrow down the direction in the sky that the waves came from. The researchers could say only that the signal was from a wide region that covers roughly one quarter of the sky. They narrowed down the region slightly the day after.

Still, astronomers had well-honed machines for doing just this type of search, and the data they collected the following night should ultimately reveal the source, Kasliwal says. "If it existed in that region, there's no way we would have missed it."

In the 2017 neutron-star merger, the combination of observations in different wavelengths produced a stupendous amount of science. Two seconds after the event, an orbiting telescope had detected a burst of gamma rays—presumably released when the merged star collapsed into a black hole. And some 70 other observatories were busy for months, watching the event unfold across the electromagnetic spectrum, from radio waves to x-rays.

If the April 26 event is not a black hole–neutron star merger, it is probably also a collision of neutron stars, which would bring the total detections of this type up to three.

LONG-SOUGHT SYSTEM

But seeing a black hole sweep up a neutron star could produce a wealth of information that no other type of event can provide, says B. S. Sathyaprakash, a LIGO theoretical physicist at Pennsylvania State. To begin with, it confirms that these long-sought systems do exist, originating from binary stars of very different masses.

And the orbits the two objects trace in the final phases of their approach could be rather different from those seen with pairs of black holes. In the neutron star–black hole case, the more massive black hole would twist space around it as it spins. “The neutron star will be swirled around in a spherical orbit rather than a quasicircular orbit,” Sathyaprakash says. For this reason, “neutron star–black hole systems can be more powerful test beds for general relativity,” he says.

Moreover, the gravitational waves and the companion observations from astronomers could reveal what happens in the final phases before the merger. As tidal forces tear the neutron star apart, they could help astrophysicists solve a long-standing mystery: what state is matter in inside these ultracompact objects?

The LIGO-Virgo collaboration began its current observing run on April 1 and had expected to see roughly one merger of black holes per week and one of neutron stars per month. So far, those predictions have been met—the observatories have also seen several black hole mergers this month. “This is just amazing,” says Kasliwal. “The universe is fantastic.”

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—Davide Castelvecchi

China Reveals Scientific Experiments for Next Space Station

Projects will probe topics including DNA mutation, fire behavior and the birth of stars

A full-scale replica of the "Tianhe" core module for China's next space station, displayed during a Chinese airshow in late 2018.

LONG WEI *GETTY IMAGES*

CHINA HAS SELECTED nine scientific experiments—including a project that will probe how DNA mutates in space—to fly on its first major space station, scheduled to be completed in 2022.

The China Manned Space Agency selected the projects, which involve scientists from 17 nations, from 42 hopefuls, in a process organized with the United Nations Office for Outer Space Affairs (UNOOSA).

China’s existing space laboratory, Tiangong-2, which launched in 2016, also hosts experiments, but the new space station will be bigger and is intended to last longer. Known as the China Space Station, the outpost will be less than one quarter of the mass of the International Space Station (ISS).

The science projects cover similar topics to experiments that have flown on the ISS since its launch in 1998, including fluid and fire behavior, biology and astronomy.

Scientists working on the projects hail from spacefaring nations such as Russia, Japan and India, as well as low- and middle-income countries, including Kenya, Mexico and Peru—the result of a special effort to encourage participation from such nations. “The cooperation takes into account the special needs of developing countries, which were encouraged to submit joint project applications with developed countries,” said Wang Qun, China’s ambassador to the United Nations in Vienna, in a statement.

The experiments include an Indian-Russian observatory called Spectroscopic Investigations of Nebular Gas, which will map dust clouds and star-forming regions of space using ultraviolet light. A group of European institutions, meanwhile, will study how microgravity and radiation in space affect the mutation of DNA in human “organoids”—3-D biological structures that mimic organs. And a Saudi Arabian team will test how solar cells perform on the outside of the space station.

Other winners include a detector

called POLAR-2, a more powerful follow-up to a sensor launched on Tiangong-2 to study the polarization of energetic γ-ray bursts from distant cosmic phenomena. POLAR-2, which will be built by an international collaboration, could even allow astronomers to observe the weak radiation associated with sources of gravitational waves.

But none of the experiments come from the United States, which since 2011 has forbidden NASA researchers from collaborating with China without congressional approval. A spokesperson for UNOOSA told *Nature* that U.S. scientists were eligible to take part and were involved in several applications, but those projects weren't ultimately selected.

The United States is planning to cut its funding for the ISS from 2024, as it concentrates its space efforts on building an outpost in the moon's orbit from 2022. This could mean that the Chinese space station becomes scientists' only laboratory in low Earth orbit from 2024.

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—Elizabeth Gibney

Large Hadron Collider Beauty (LHCb) experiment at CERN.

CERN

What Happened to All of the Universe's Antimatter?

Differences between matter and antimatter could help explain why the cosmos mostly lacks the latter today, researchers say

WE COULD HAVE BEEN living in an antimatter universe, but we are not. Antimatter is matter's upside-down twin—every matter particle has a matching antimatter version with the opposite charge. Physicists think the cosmos started out with just as much antimatter as matter, but most of the former got wiped out. Now they may be one step closer to knowing why.

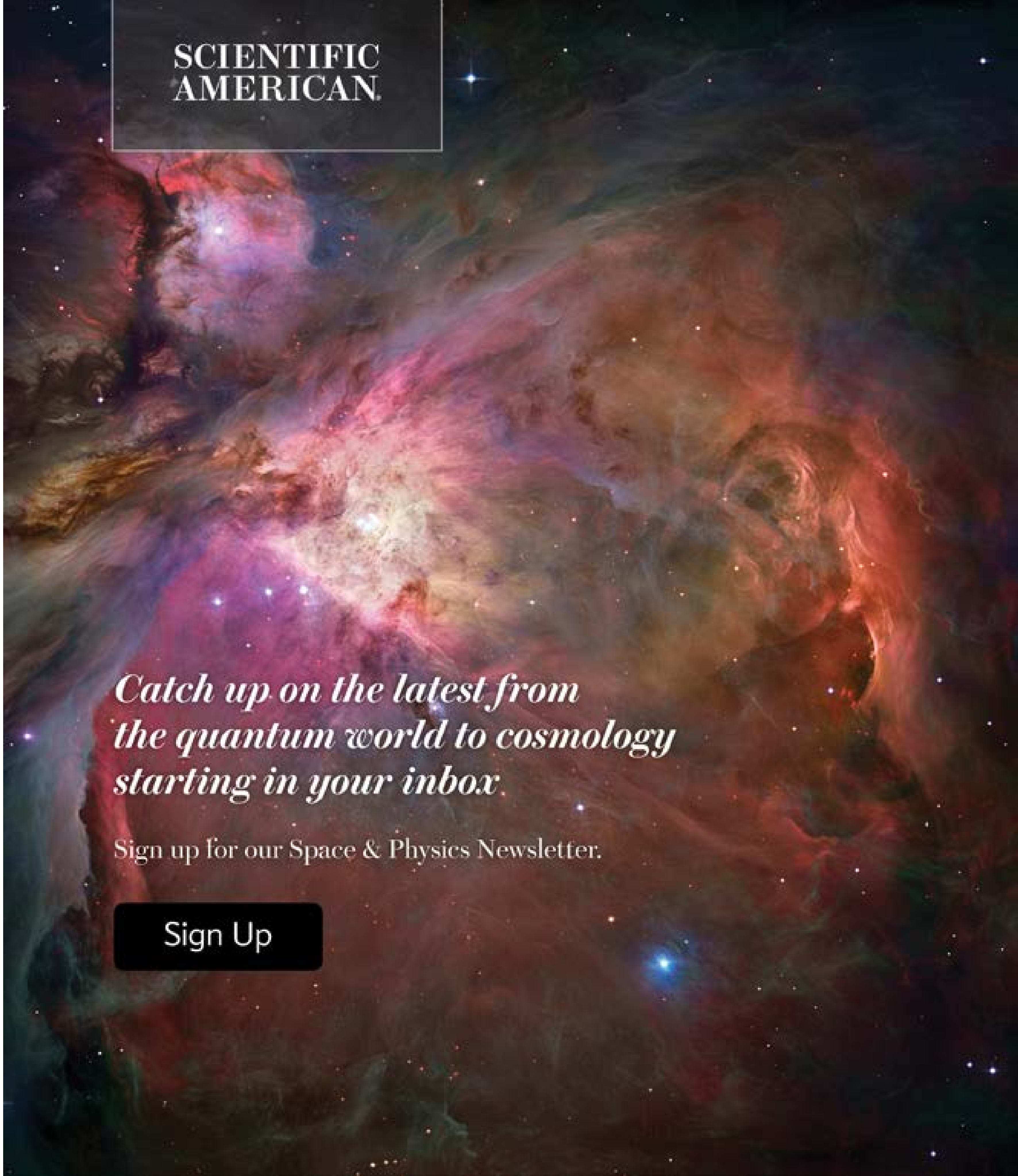
Researchers at the Large Hadron Collider Beauty (LHCb) experiment at CERN near Geneva have discovered antimatter and matter versions of "charm" quarks—one of six types, or flavors, of a class of elementary matter particles—acting differently from one another. In a new study, which was presented in March at the "Rencontres de Moriond" particle physics conference in La Thuile, Italy, the physicists found that unstable particles called D^0 mesons (which contain charm quarks) decayed into more stable particles at a slightly different rate than their antimatter counterparts. Such differences could help explain how an asymmetry arose between matter and antimatter after the big bang, resulting in a universe composed mostly of matter.

Matter and antimatter annihilate each other on contact, and researchers believe such collisions destroyed almost all of the antimatter (and a large chunk of the matter) that initially existed in the cosmos. But they do not understand why a relatively small excess of matter survived to become the stars and planets and the rest of the cosmos. Consequently, physicists have been looking for a kind of matter that behaves so differently from its antimatter version that it would have had time to generate this excess in the early universe.

The newly discovered mismatch in decay rates between charm quarks and antiquarks turns out to be too small to account for the universe's excess of matter. The result, however, "does bring us closer to finding the answer because it shows one of the possible answers may not be the right one," says theoretical physicist Yuval Grossman of Cornell University, who was not involved in the new work. "I am also excited because it's the first time we've ever seen this [phenomenon in charm quarks]."

Physicists previously found similar variations in two other quark flavors, but those were also too tiny to account for our matter-dominated universe. Scientists are holding out hope of finding much larger matter-antimatter differences elsewhere, such as in ghostly particles called neutrinos or reactions involving the Higgs boson—the particle that gives others mass—says LHCb team member Sheldon Stone of Syracuse University: "There are lots of different searches going on."

—Clara Moskowitz



New Space Telescope Will Map the Universe in High-Energy X-rays

A German-Russian mission called SRG will detect millions of supermassive black holes, many new to science, and hundreds of thousands of stars

By Davide Castelvecchi

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Davide Castelvecchi is a senior reporter at *Nature* in London covering physics, astronomy, mathematics and computer science.

“HAVE YOU SEEN YOUR BODY IN X-RAYS? IT LOOKS COMpletely different,” says Rashid Sunyaev. “We will do the same with the universe.” Sunyaev, an eminent Soviet-born cosmologist at the Max Planck Institute for Astrophysics in Garching, Germany, could be about to get his long-held wish.

On July 13, a joint German–Russian mission called Spectrum-Roentgen-Gamma (SRG) launched into space to chart an unprecedented map. It won’t be the first space telescope sensitive to high-energy “hard” x-rays, which offer astrophysicists a window into otherwise faint objects in the universe. But it will be the first able to create a full map of the sky in this part of the spectrum—one that will give researchers a new way to track the universe’s expansion and acceleration over the eons. “Within a half year, we will cover the whole sky,” says Peter Predehl, an x-ray astronomer at the Max Planck Institute for Extraterrestrial Physics, also in Garching, and a principal investigator for the mission.

SRG’s main scientific goal is cosmological: to create a 3-D map of the cosmos that will reveal how the universe accelerates under the mysterious repulsive force called dark energy. Cosmologists can probe this force through galactic clusters, whose distribution encodes the structure and history of the universe. SRG will map a cosmic web of about 100,000 galactic clusters by detecting the x-ray glow from their intergalactic plasma and from the plasma filaments that join them. The mission will also detect up to three million supermassive black holes—many of which will be new to science—and x-rays from as many as 700,000 stars in the Milky Way.

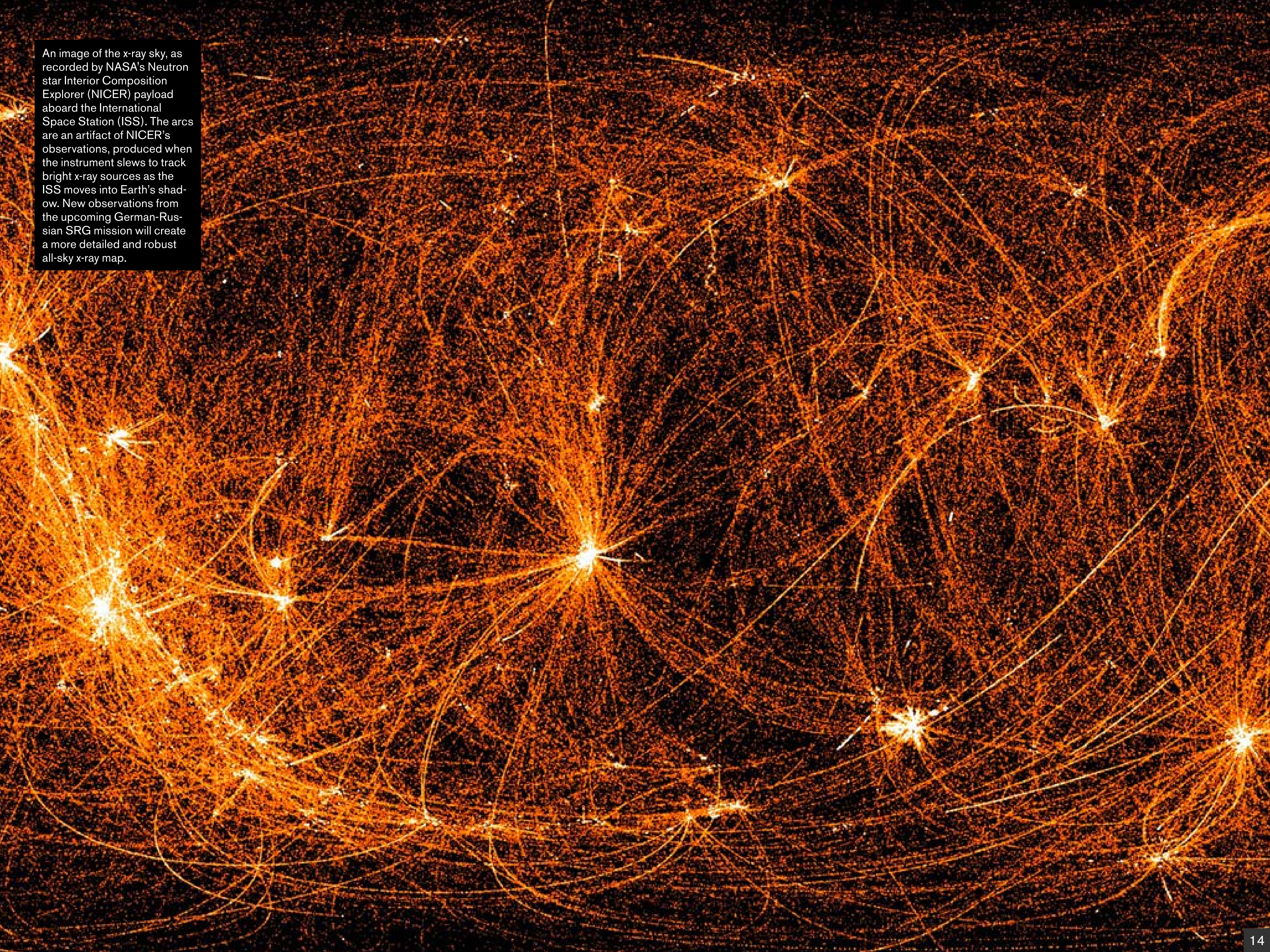
“It’s going to be a great survey,” says x-ray astronomer Giuseppina Fabbiano of the Harvard–Smithsonian Center for Astrophysics in Cambridge, Mass. Its data will have a unique role in the field for a long time, she adds.

RUSSIAN RESURRECTION

For Russia, SRG represents one of the most significant space science missions for decades, and it aims to bolster the country’s astrophysics community, which has suffered decades of cuts and brain drain. The mission carries two independent x-ray telescopes: a German-built one called eROSITA (Extended Roentgen Survey with an Imaging Telescope Array) and a Russian-built one called ART-XC (Astronomical Roentgen Telescope—X-ray Concentrator), which is the first instrument of its kind in the history of Russian and Soviet space research, says Mikhail Pavlinsky, a high-energy astrophysicist at the Russian Academy of Sciences Space Research Institute in Moscow and principal investigator on ART-XC. “Now we have a new chance to return to world-class science,” he says.

The spacecraft lifted off on a Russian-built Proton-M rocket from the Baikonur Cosmodrome in Kazakhstan. X-ray sky surveys have been conducted by previous missions, including one from Germany in the 1990s, called ROSAT. But that mission was sensitive only to “soft” x-rays, with energies of about two kiloelectronvolts (keV). Existing missions, such as NASA’s Chandra X-ray Observatory and NuSTAR, can see higher-energy radiation and resolve tiny details of cosmic structures, but they see only small parts of the sky.

SRG’s two instruments each cover x-ray bands that stretch to much higher energies: 0.2 to 10 keV for eROSITA, and five to 30 keV for ART-XC. (Despite its name—which was kept for historical reasons—SRG will not detect gamma radiation.) Each instrument is a bundle of seven x-ray telescopes that will frame the same swath of sky simultaneously; their combined power means that they will collect more photons than a single telescope. X-ray photons from the sky are few and far between, so



An image of the x-ray sky, as recorded by NASA's Neutron star Interior Composition Explorer (NICER) payload aboard the International Space Station (ISS). The arcs are an artifact of NICER's observations, produced when the instrument slews to track bright x-ray sources as the ISS moves into Earth's shadow. New observations from the upcoming German-Russian SRG mission will create a more detailed and robust all-sky x-ray map.

the telescopes' semiconductor-based sensors—higher-energy versions of the sensors in ordinary digital cameras—will also be able to estimate the amount of energy contained in individual photons.

During its planned four-year mission, SRG will map the entire sky eight times, and researchers will compare the maps and look for changes. For instance, some of the supermassive black holes at galactic centers become extremely bright when they devour matter at a high rate and then go back to relative quiescence. Although most soft x-rays from these black holes are likely to be absorbed by surrounding dust, harder x-rays should get through, says Pavlinsky. ART-XC might see the objects appearing and then disappearing again from one year to the next, providing information about how black holes consume matter. "We wish to observe several thousand of these events during these four years," Sunyaev says.

SRG will also investigate the universe's distrubtion of ordinary matter and dark matter—the main engine of galaxy formation—and look for direct hints as to the nature of dark matter particles. It will do this by trying to confirm previous signals that showed peaks in x-ray emissions from some galactic centers, which some researchers have suggested come from the decay of an unknown, heavier relative of the known subatomic particles called neutrinos. These neutrinos could be a major component of dark matter, they suggest—although this interpretation is controversial. "So far, the dark matter explanation is still on the table" as a potential cause of the x-ray signal, says Esra Bulbul, an astrophysicist at the Max Planck Institute for Extraterrestrial Physics and a lead scientist on the mission.

> **"So far, the dark matter explanation is still on the table" as a potential cause of the x-ray signal.**
> **—*Esra Bulbul***

A LONG TIME COMING

A hard x-ray space mission has long been on the cards for Russian and German astrophysicists: SRG's roots stretch back to the Soviet Union. In 1987, leading astrophysicists, including Sunyaev—with his mentors Yakov Zeldovich and Andrei Sacharov—proposed a major mission using hard x-rays, but plans were canceled after the Soviet Union fell in 1991.

The European and Russian space agencies revived the idea in 2004, but a proposal to send an x-ray telescope to the International Space Station was scrapped when NASA whittled down its space shuttle program, ultimately ending it in 2011. The German space agency and Roscosmos later approved a joint mission, and more ambitious design, in 2009.

"There have been many, many ups and down until the whole thing really came out of the woods," says Predehl.

Unusually, the mission has a special data arrangement that aims to support Russia's small astrophysics community. Instead of putting the data in one repository, as is typical for such missions, German researchers will store and analyze data on one half of the sky (the part west of the galactic center) and Russian scientists will do the same with the other half, giving them dedicated time to work on the data, says Sunyaev. The mission will later open the data to other researchers.

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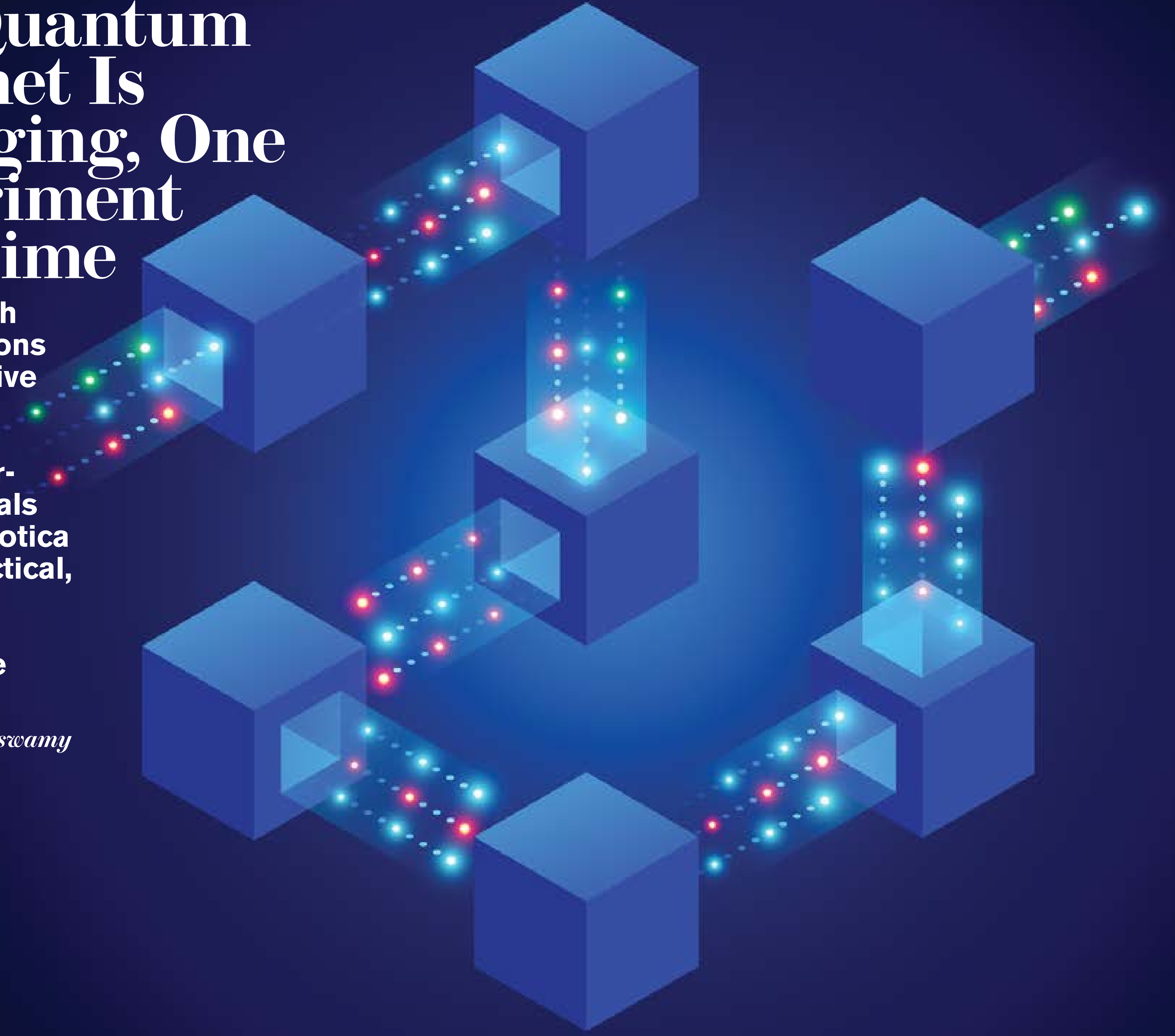
The Quantum Internet Is Emerging, One Experiment at a Time

Breakthrough demonstrations using defective diamonds, high-flying drones, laser-bathed crystals and other exotica suggest practical, unhackable quantum networks are within reach

By Anil Ananthaswamy



OLENA OSTAPENKO *GETTY IMAGES*

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

TODAY'S INTERNET IS A PLAYGROUND FOR HACKERS. From insecure communication links to inadequately guarded data in the cloud, vulnerabilities are everywhere. But if quantum physicists have their way, such weaknesses will soon go the way of the dodo.

They want to build quantum networks sporting full-blown quantumness, where information is created, stored and moved around in ways that mirror the bizarre behavior of the quantum world—think of the metaphorical cats that can be both dead and alive or particles that can exert "spooky action at a distance." Freed from many limitations of "classical" networks, these systems could provide a level of privacy, security and computational clout that is impossible to achieve with today's Internet.

Although a fully realized quantum network is still a far-off vision, recent breakthroughs in transmitting, storing and manipulating quantum information have convinced some physicists that a simple proof-of-principle is imminent.

From defects in diamonds and crystals that help photons change color to drones that serve as spooky network nodes, researchers are using a smorgasbord of exotic materials and techniques in this quantum quest. The first stage, many say, would be a quantum network using standard optical fiber to connect at least three small quantum devices about 50 to 100 kilometers apart.

Such a network may be built in the next five years, according to Ben Lanyon of the Institute for Quantum Optics and Quantum Information in Innsbruck, Austria. Lanyon's team is part of Europe's Quantum Internet Alliance, coordinated by Stephanie Wehner at the Delft University of Technology in the Netherlands, which is tasked with creating a quantum network. Europe is competing with similar national efforts in China—which in 2016 launched Micius, a quantum communications satellite—as well as in the United States. Last December, the U.S. government enacted the National Quantum Initiative Act, which will lavishly fund a number of research hubs dedicated to quantum technologies, including quantum computers and networks. "The main feature of a quantum network is that you are sending quantum information instead of classical information," says Delft University's Ronald Hanson. Classical information deals in bits that have values of either 0 or 1. Quantum information, however, uses quantum bits, or qubits, which can be in a superposition of both 0 and 1 at the same time. Qubits can be encoded, for example, in the polarization states of a photon or in the spin states of electrons and atomic nuclei.

QUANTUM NETWORKING

In what Hanson calls the "low hanging fruit of quantum networks," qubits are already being used for creating secret keys—random strings of 0s and 1s—that can then be used to encode classical information, an application called quantum key distribution (QKD).

QKD involves one party, say Alice, sending qubits to Bob, who measures the qubits (Alice and Bob first appeared in a 1978 paper on public key cryptography and have now become placeholders for nodes in a quantum network). Only for certain types of measurements will Bob get the same value that Alice encoded in the qubits. Alice and Bob can compare notes over a public channel to figure out what those measurements are, without actually sharing the qubit values. They can then use those private values to create a secret shared key to encrypt classical messages. Crucially, if an intruder were to intercept the qubits, Alice and Bob could detect the intrusion, discard the qubits and start over—theoretically continuing until no one is eavesdropping on the quantum channel.

In July last year, Alberto Boaron of the University of Geneva, Switzerland, and colleagues reported distributing secret keys using QKD over a record distance of more than 400 kilometers of optical fiber, at 6.5 kilobits per second. In contrast, commercially available systems, such as the one sold by the Geneva-based company ID Quantique, provide QKD over 50 kilometers of fiber.

ALICE AND BOB GET SPOOKY

Ideally, quantum networks will do more than QKD. The next step would be to transfer quantum states directly between nodes. Whereas qubits encoded using a photon's polarization can be sent over optical fibers (as is done with QKD), using such qubits to transfer large amounts of quantum information is problematic. Photons can get scattered or absorbed along the way or may simply fail to register in a detector, making for an unreliable transmission channel. Fortunately, there is a more robust way to exchange quantum information—via the use of another property of quantum systems, called entanglement.

When two particles or quantum systems interact, they can get entangled. Once entangled, both systems are described by a single quantum state, so measuring the state of one system instantly influences the state of the other, even if they are kilometers apart. Einstein called entanglement "spooky action at a distance," and it is an invaluable resource for quantum networks. Imagine two network nodes, Alice and Bob, each made of some isolated bit of matter (the most obvious and reliable substrate for encoding and storing quantum states). Such "matter nodes" can become entangled with each other via a process that involves the exchange of entangled photons.

Using entangled matter nodes, Alice can exploit her share of the entanglement to send an entire qubit to Bob, without actually transmitting a physical qubit, making the transfer foolproof and secure. The key here is that once entanglement is established between the nodes, the protocol to transfer qubits from Alice to Bob is robust and deterministic.

But to do this across long distances, one first needs to distribute the entanglement—usually via standard fiber-optic networks. In January, Lanyon's team in Innsbruck reported setting the record for creating entanglement between matter and light over 50 kilometers of optical fiber.

For matter, Lanyon's team used a so-called trapped ion—a single calcium ion confined to an optical cavity using electromagnetic fields. When manipulated with lasers, the ion ends up encoding a qubit as a superposition of two energy states, while also emitting a photon, with a qubit encoded in its polarization states. The qubits in the ion and the photon are entangled. The task: to send this photon through an optical fiber while preserving the entanglement.

> **"We are now building two of these nodes. We'll use glass fiber that's already in the ground to entangle these two nitrogen-vacancy centers."**
> ***—Ronald Hanson***

Unfortunately, the trapped ion emits a photon at a wavelength of 854 nanometers (nm), which does not last long inside an optical fiber. So, Lanyon's team sent the emitted photon into something called a nonlinear crystal being pumped with a powerful laser. The entire interaction converts the incoming photon into another of "telecom" wavelength, one well suited for optical fibers.

The Innsbruck team then injected this photon into a 50-kilometer-long section of optical fiber. Once it reached the other end, they tested the ion and the photon to see if they were still entangled. They were.

SWAPPING ENTANGLEMENTS

Lanyon's team now wants to entangle two trapped ion nodes that are 100 kilometers apart. Each node would transmit an entangled photon through 50 kilometers of optical fiber to a station in the middle. There, the photons would be measured in such a way that they lose entanglement with their respective ions, causing the ions themselves to get entangled with each other. As a consequence, the two nodes, 100 kilometers apart, will each form a quantum link via a pair of entangled qubits. The entire process is called entanglement swapping. Although relatively inefficient for now, Lanyon calls the setup "a good start" for developing better, faster swapping systems.

Meanwhile, Hanson's team at Delft has demonstrated how to entangle a different type of matter node with a telecom-wavelength photon. They used a defect in diamond called a nitrogen-vacancy (NV) center. The defect arises when a nitrogen atom replaces a carbon atom in the gem's crystalline structure, leaving a vacancy in the crystal lattice adjacent to the nitrogen atom. The team used lasers to manipulate the spin of one "free" electron in the diamond NV center, placing the electron in a superposition of spin states, thus encoding one qubit. The process also results in the emission of a photon. The photon is in a superposition of being emitted in one of two consecutive time slots. "The photon is always there, but in a superposition of being emitted early or late," says Hanson. The qubit stored in the electron's spin and the qubit stored in the photon's presence or absence in the time slots are now entangled.

In 2015, the Delft team placed two spatially separated matter nodes made of diamond NV centers about 1.3 kilometers apart, linked by optical fiber. The team then transmitted an entangled photon from each node to a point roughly midway on the path between these two nodes. There, the team swapped the entanglement, causing the two NV centers to become entangled. But, just as with Lanyon's experiment, the photons emitted by the Delft team's apparatus have a wavelength of 637 nm. Such photons are terrible travelers when injected into optical fibers, diminishing in intensity by an order of magnitude for every kilometer they travel. "It makes it impossible to go beyond a few kilometers," says Hanson.

So, in May, the Delft team reported a remedy similar to that developed by the Innsbruck team, also using nonlinear crystals and lasers to convert the photon to telecom wavelengths. In this approach, the qubits encoded by the NV center and telecom-wavelength photon remained entangled, setting the stage for entanglement swapping between two diamond NV center nodes.

Although they have not yet transmitted a diamond-entangled telecom-wavelength photon through any significant length of optical fiber, Hanson is confident that they can do so and then entangle diamond NV centers 30 kilometers apart using entanglement swapping. "We are now building two of these nodes," he says. "We'll use glass fiber that's already in the ground to entangle these two NV centers." Their next goal is to entangle nodes using the preexisting fiber infrastructure among three cities in the Netherlands, where distances are amenable to such state-of-the-art experiments.

> **"It's always good to be able to connect different hybrid systems."**
> ***—Marcelli Grimau Puigbert***

MIX AND MATCH: THE CHALLENGE AHEAD

The Innsbruck and Delft teams each worked with only one type of matter for storing and entangling qubits. But real-life quantum networks may use different types of materials in each node, depending on the exact task at hand—for example, quantum computation or quantum sensing. And quantum nodes, besides manipulating qubits, may also have to store them for brief periods, in so-called quantum memories.

"It's still not clear what's going to be the right platform and the right protocol," says Marcelli Grimau Puigibert of the University of Basel in Switzerland. "It's always good to be able to connect different hybrid systems."

To this end, Puigibert, working with Wolfgang Tittel's team at the University of Calgary, recently showed how to entangle qubits stored in two different types of materials. They started with a source that emits a pair of entangled photons, one at a wavelength of 794 nm and the other at 1,535 nm. The 794-nm photon interacts with a lithium-niobate crystal doped with thulium, so that the photon's state becomes stored in the crystal. The 1,535-nm photon goes into an erbium-doped fiber, which also stores the quantum state.

Both memories were designed to reemit photons at a particular time. The team analyzed those reemitted photons and showed that they remained entangled. This, in turn, implies that the quantum memories were also entangled just prior to emitting those photons, thus preserving entanglement over time.

The photon wavelengths were also designed to cross-connect different transmission systems: optical fibers on one end (1,535 nm) and satellite communications on the other (794 nm). The latter is important because if quantum networks are to go intercontinental, entanglement will need to be distributed via satellites. In 2017, a team led by Jian-Wei Pan of the University of Science and Technology of China in Hefei used Micius, China's quantum satellite, to distribute entanglement between ground stations on the Tibetan Plateau and southwest China.

Satellites, however, seem destined to remain an expensive, niche option of last resort for quantum networks. The next best choice may be relatively inexpensive drones. In May, Shi-Ning Zhu of Nanjing University and colleagues reported that they had used a 35-kilogram drone to send entangled photons to two quantum nodes 200 meters apart on the ground. The experiment used a classical communication link between the nodes to confirm that the photons they received were indeed entangled. The experiment succeeded in significantly varying conditions, working in sunlight and in darkness and even on rainy nights. If such drones can be scaled up and installed on high-altitude unmanned aerial vehicles, the distance between the nodes on the ground can extend to about 300 kilometers, the authors write.

Challenges remain in the march toward a fully functioning quantum network. Reliable quantum memories are one. Another important missing piece is the ability to extend the reach of a quantum link to arbitrarily long distances, using so-called quantum repeaters. Quantum states cannot be simply copied and regurgitated, as is done with classical information. Quantum nodes will need sophisticated quantum logic gates to ensure that entanglement is preserved in the face of losses due to interaction with the environment. "It's definitely one of the next big challenges," says Lanyon.

Nonetheless, the basic elements are falling into place for building a quantum network that connects at least three cities—and, perhaps, eventually the world. "We now have platforms with which we can start to explore true quantum networks for the first time," says Hanson. More sophisticated networks beckon. "There's no guarantee. There's only promise there [of] the cool stuff we'll be able to do if we succeed."

Venus, Earth's Evil Twin, Beckons Space Agencies

Once a water-rich Eden, the hellish planet could reveal how to find habitable worlds around distant stars

By Shannon Hall

Venus silhouetted against the sun, as seen by Japan's Hinode spacecraft in 2012. The planet's atmosphere appears as a thin, glowing crescent on the disk's upper left.

JAXA, NASA AND HINODE

Shannon Hall is an award-winning freelance science journalist based in the Rocky Mountains. She specializes in writing about astronomy, geology and the environment.

THE HELICOPTER FELL LIKE A STONE. IT dropped by more than 1,500 meters over Md, twisting slightly as the ground grew rapidly closer. Although this was all according to plan, that didn't settle James Garvin's nerves. Nor did the realization that his seat belt wasn't fully fastened—a moment that sent his heart rate skyrocketing.

Then, a mere six meters above the ground, the ride got even wilder when the pilots pulled the aircraft out of the fall and climbed skywards, only to fall again. The helicopter dropped 10 times that day. And each time, Garvin pointed a camera toward the ground through the open door in an attempt to measure the topography of a rock quarry below—from massive boulders to smooth sheets of sand. Although his interests were hardly terrestrial.

Garvin, the chief scientist at NASA's Goddard Space Flight Center in Greenbelt, Md., is the principal investigator on a proposed mission to Venus that would drop a probe through its atmosphere. That's why he hired two pilots in August 2016 to plunge a helicopter toward the ground while he tested what a Venus probe might be able to photograph. The harrowing ride was worth it: researchers would love to get their hands on pictures of Venus with so much detail that the scenery would become familiar. "These images would be like you landing in your backyard," he says.

Garvin is not the only scientist preparing such a daring mission. Nearly every space agency around the globe is currently sketching a proposal to explore our long-neglected neighbor. The Indian Space Research Organization (ISRO) will be the first to lift off when it launches an orbiter to Venus in 2023. The United States could follow close behind. Garvin and his colleagues are one of a handful of groups that will soon propose missions to NASA that, if selected, would take off in 2025. The European Space Agency (ESA) is currently considering a proposal to send an orbiter to Venus in 2032. And the Russian space agency Roscosmos is working in collaboration with the United States to send a daring mission to the planet any time from 2026 to 2033, which would include an orbiter, a lander that would send back short-term readings and a research station that would survive for much longer.

The newfound interest stands in stark contrast to the fact that nations have long overlooked Venus in favor of chasing Mars, asteroids and other planets. Over the past 65 years, for example, NASA has sent 11 orbiters and eight landers to Mars, but just two orbiters to Venus—and none since 1994. This has not been for lack of scientific interest. Since the mid-1990s, U.S. scientists alone have submitted nearly 30 Venus proposals to NASA. None has been approved.

But momentum is building to explore Venus, in part because scientists say it could hold the secret to understanding what makes a planet habitable. Once Earth's twin, today Venus is a hellish abode where surface temperatures reach more than 400 degrees Celsius, atmospheric pressures slam down with enough force to crush heavy machinery and clouds of sulfuric acid blow through the sky. If researchers could decipher why conditions on Venus turned so deadly, that would help them to assess whether life might exist on some of the thousand-plus rocky worlds that astronomers are discovering throughout the galaxy.

As the scientific justification has grown for exploring Venus, planetary scientists are dreaming up new ways to study the planet and are building technology in the laboratory that can survive the horrendous conditions on its surface. And with India leading the way, there might soon be a parade of probes heading toward the second rock from the sun.

"It might be the start of a new decade of Venus," says Thomas Widemann, a planetary scientist at the Paris Observatory.

DOUBLE TROUBLE

When humanity initially reached toward the stars, it ventured to Venus. Our neighbor was the target of the first successful interplanetary probe (United States, 1962); the first planet on which a mission crashed (Soviet Union, 1965); and the first alien world to host a successful landing (Soviet Union, 1970). It was during this space race to Venus that scientists discovered a torrid and toxic world. That could explain why interest in Venus dwindled. Scientists quickly realized that this planet would not be a home for future human exploration nor an outlet on which to search for life. It would be downright difficult to study at all, even for short amounts of time.

And yet, in so many ways—size, density, chemical makeup—Venus is Earth's double. Recent research has even suggested that it might have looked like Earth for three billion years, with vast oceans that could have been friendly to life. "That's what sets my imagination on fire," says Darby Dyar, a planetary scientist at Mount Holyoke College. "If that's the case, there was plenty of time for evolution to kick into action."

That could mean that Venus was (somewhat surprisingly) the first habitable planet in the solar system—a place where life was just as likely to arise as it was on Earth. That alone is a reason to return to the former ocean world. "Why are we investing so much time looking for life on Mars when it only had liquid water for 400 million years?" Dyar asks. "And then there's Venus with three billion years of water and no one loves her."

Yet there's no question that something went terribly wrong. Although Earth and Venus began in a similar fashion, the two have wandered down drastically different evolutionary paths—diverging perhaps as recently as 715 million years ago. That might seem like a reason not to visit, but scientists now argue that it makes the planet even more intriguing. If researchers could only understand what caused Venus to undergo such a deadly metamorphosis, they might gain a better understanding of what caused Earth to become such a haven for life.

"Venus plays a key role in understanding ourselves here—how life evolved on our own planet," says Adriana Ocampo, science program manager at NASA headquarters in Washington, D.C.

It is a crucial question now that astronomers have uncovered thousands of planets outside our solar system—many of which are rocky worlds that orbit their stars at distances similar to those of Venus and Earth from the sun. That means that many of these worlds could be Venus-like. "There is growing realization within the exoplanet community that Venus is the best analogue in the solar system for many of the rocky exoplanets we have found," says Laura Schaefer, an astronomer at Stanford University, who studies exoplanets.

OFF THE RADAR

With such a tantalizing question left unanswered, it's easy to see why ISRO's return to Venus has created so much excitement. "I'm thrilled that ISRO is doing this," Dyar says. "I'm thrilled that the international community is taking note of Venus and proposing missions. That's fantastic."

Although the ISRO mission is enveloped in a cloud of secrecy (*Nature* e-mailed and called project scientists dozens of times, to no avail), it's clear that the agency plans to send an orbiter smothered in instruments. When ISRO announced the mission late last year, it published a list of a dozen instruments proposed by Indian scientists that have already been chosen—providing a sneak peek of the mission. Of those sensors, two will map the planet using radar, which is arguably the best method to peer through Venus's dense clouds and trace its surface from orbit.

That said, ISRO is a relatively young space agency with a limited number of successful landings on the moon and Mars. And, similar to programs from other fledgling agencies, India's first Venus mission might be a proof of concept that is less focused on science than on engineering. But given that even basic information on Venus is lacking, any small step will contribute to science.

One such contribution might be new maps of Venus's surface features—a major step up, scientifically. The last mission to map the planet's topography was NASA's Magellan orbiter, which launched 30 years ago. Although those radar maps remain the foundation of Venusian geoscience today, they show topographic details at a horizontal resolution of just 10 to 20 kilometers per pixel, on average (the image resolution can be two orders of magnitude higher). With such limited topographic data, researchers have a blurry view of Venus's geology—but the available maps do hint that plate tectonics might be kicking into action today.

That is particularly tantalizing, because many scientists think that tectonic activity is a crucial ingredient for life. Tectonic plates—those interlocking slabs of Earth's crust that fit together like puzzle pieces—constantly move about, with some slipping below others and diving into the planet's interior in a process called subduction. Over millions of years, that process has kept Earth from growing too hot or cold by cycling heat-trapping carbon dioxide between the atmosphere and the deep Earth. It acts as a natural thermostat, which might mean that fidgety planets are more likely to host life.

As such, scientists are eager to decipher the conditions that allow plate tectonics to arise. That is why Suzanne Smrekar, a planetary scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif., has her eye on Venus—especially some spots that look eerily similar to locations on Earth where subduction is happening now. Scientists agree that subduction is the first step in the path toward plate tectonics, and yet there are no clear signs of large moving plates on Venus—at least not in the decades-old maps produced by Magellan. The San Andreas fault, which forms the tectonic boundary between Earth's Pacific Plate and North American Plate, for example, varies in width from meters to a kilometer—too narrow to show up in Magellan topographic data.

But future maps might uncloak such tectonic features. Smrekar is the principal investigator on a potential mission, known as VERITAS, that she and her team will soon propose to NASA. The geophysical mission would use radar to map Venus's topography in higher resolution than before—increasing the accuracy from roughly 15 kilometers to 250 meters—and allowing scientists to uncover features as small as the San Andreas fault for the first time.

Although scientists don't know what they will find, it is possible that they will uncover evidence for past plate tectonics. Such a discovery would explain why Venus preserved an Earth-like environment for billions of years, Smrekar says—that natural thermostat would have kept CO_2 in check. And it would explain how Venus turned hellish. When plate tectonics ceased, CO_2 levels would have increased in the atmosphere and trapped so much heat that the oceans vaporized.

But that is only one possible finding. Some scientists are keen to study the planet's atmosphere, which holds another, equally tantalizing set of secrets.

"Why are we investing so much time looking for life on Mars when it only had liquid water for 400 million years?"
—Darby Dyar

The probe that Garvin is proposing, called DAVINCI, would drop through the atmosphere to measure the brew of toxic compounds. The isotopes of noble gases, particularly xenon, could give scientists a window into the planet's volcanic history and reveal whether Venus started with as much water as Earth did. "Venus's atmosphere is this lurking laboratory for telling us about its history," Garvin says. "And really, most of the measurements in the atmosphere are woefully incomplete." In addition, the probe would take images of the surface—thanks to Garvin's terrifying helicopter flights—until the last few seconds before it hits.

Both VERITAS and DAVINCI entered NASA's competition in July for future Discovery missions—a line of low-cost planetary probes that each cost just U.S.$500 million. And rumor has it they're not alone. There could be as many as five Venus missions (including a balloon) among the dozens of proposals to study various objects in space. NASA's last Discovery competition, in 2015, for example, considered 27 proposals—from probes that would explore asteroids, moons and planets across the solar system to telescopes that would image its outer reaches—before choosing two missions that would fly.

At the end of this year, the administration will select a few missions for further study, and it will pick the final project in two years' time. Both Smrekar and Garvin are hopeful that each of their missions will be selected, in part because they proposed similar missions in the last Discovery competition, and both were chosen for further study, along with three others. If one of the Venus missions is successful, it will launch in the mid-2020s.

Even after that time frame, Venus might remain a hub for interplanetary activity. ESA recently picked a Venus probe called EnVision, along with two other finalists, as a mission that could fly as soon as 2032. Like VERITAS, EnVision is an orbiter. But unlike VERITAS, which would map the entire planet to a resolution of 15 to 30 meters, EnVision will analyze small portions of the planet with a resolution as high as one meter. At that level of accuracy, scientists might be able to see the landers that the Soviet Union left behind.

They could even pick out the type of rock that the landers are resting on. This is possible because astronomers in the early 1990s found that certain wavelengths of light can pass through the CO_2 haze that hides the Venusian surface. An orbiter carrying a spectrometer tuned to these transparent "windows" in the light spectrum could analyze the composition of the planet's surface from above the clouds. That's an exciting prospect, especially if scientists could spot granite.

Like basalt, granite forms when molten magma cools and hardens. But unlike basalt, the recipe for granite typically requires copious amounts of water—which happens on Earth when water-rich oceanic crust subducts below another plate. So if Venus is found to be rich in granite, it probably once overflowed with liquid water.

And that might be the best hint yet that the planet was formerly a pale blue dot vastly similar to Earth today—another clue in their diverging stories.

The problem is that there are only five narrow spectral windows in Venus's atmosphere that are actually transparent. With such little information, scientists weren't sure whether they would be able to differentiate between granite and basalt. So Jörn Helbert, a planetary scientist at the Institute of Planetary Research in Berlin, subjected both types of rock to Venus-like conditions and imaged them through those narrow frequency bands. His experiment suggested that the two rock spectra look radically different from each other, and that future missions could make use of the windows. He and his colleagues built an instrument to use this trick to map any granite on the Venusian surface. It would fly on both VERITAS and EnVision.

WITHIN REACH

To truly understand the surface, a number of scientists want to actually land a craft on our toxic twin—a feat that has not been achieved for 35 years. Although the Soviet Union sent several landers to Venus, the ones that survived quickly succumbed to the planet's harsh environment: the longest-lasting one persevered for a mere 127 minutes.

But scientists hope to break that record and have already designed technology that can last not just minutes but months. A team at NASA's Glenn Research Center in Cleveland, Ohio, is building a station that should survive for at least 60 days. Instead of using its bulk to absorb heat or countering the conditions with refrigeration, the lander would use simple electronics made of silicon carbide (a hybrid of silicon and carbon commonly used in sandpaper and fake diamonds) that can withstand the Venusian environment. "That's the real game changer for Venus exploration" says Philip Neudeck, an electronics engineer at the Glenn Research Center.

The team has already tested the circuits in a Venus simulation chamber—a 14-ton stainless-steel tank that can imitate the temperature, pressure and specific chemistry of the Venusian surface. The researchers have used those results to design a stationary surface probe called LLISSE (Long-Lived In-Situ Solar System Explorer), which should be ready for flight by the mid-2020s and will be offered to other countries. "Any mission to Venus is welcome to use LLISSE," says electronics engineer Gary Hunter, also at the Glenn Research Center. He and the team were careful to design a lander that would be only as large as a toaster—making it both small and light enough that it can hitch a ride on a number of future missions.

Despite its small size, LLISSE would be able to record temperature, pressure, wind speed, wind direction, the amount of solar energy at the surface and a few specific chemicals in the low atmosphere. And it would do so for months, providing crucial input for models of the Venusian atmosphere. "Imagine if one tried to say one knew the weather on Earth by going outside for 127 minutes," Hunter says. That is the current record for any weather data on Venus.

Already, scientists at Roscosmos are eager to use this new technology. In a joint proposal with NASA, they are working on a mission known as Venera-Dolgozhivuschaya (where the latter means long-lasting), or Venera-D for short. Such a mission would comprise a menagerie of components—an orbiter, a lander and a long-lived station. The lander would include a number of advanced instruments but would last for only a few hours; the long-lived station would be simpler in design but continue taking measurements for months. The station is likely to be NASA's LLISSE.

At least, that's the baseline architecture—but the mission could include even more. This year, the Venera-D team released a report that covered a number of potential additions, including a balloon that could explore the cloudy atmosphere. And that opens up the possibility of searching for life on Venus. All the other missions proposed so far aim to assess whether Venus was habitable in the past. But a balloon might be able to look for life in the only environment where it might survive today: the skies.

"You can imagine that there's somewhere in between the hot hostile surface and the cold vacuum of outer space where there are conditions—like Goldilocks'—that are just right for life," Dyar says. Not only would that layer have a pleasant temperature, but it could also have nutrients, liquid water and energy from the sun. If life ever existed on the planet, it might have been carried up to the clouds and survived there after the surface turned toxic.

But even without a balloon, the three main components of the Venera-D mission would provide excellent science, argues Ocampo. "It would be a breakthrough mission in the understanding of Venusian science," she says. "We haven't had a mission similar to this before."

Unfortunately, Venera-D has not yet been selected, and many scientists have expressed some concern over the fact that it has long been discussed and yet still does not have the appropriate funding. But Ludmila Zasova, the lead scientist on the Venera-D mission at the Space Research Institute in Moscow, hopes that might change this year.

It's not the only big ambitious mission in the works. Some U.S. teams plan to submit Venus projects to NASA's New Frontiers program, which is capped at $1 billion, and to the Flagship mission program, which costs even more. Because Venus proposals have done well in past competitions (often falling just behind the selected proposals), scientists think there is a good chance that they will now rise to the top.

With every space agency eyeing our neighbor, Venus is likely to receive a fleet of visitors over the next few decades. And although they all plan to address the question of habitability in one way or another, Garvin is convinced that whatever they find, it will be "beyond our wildest dreams." Perhaps they will prove that Venus was formerly an ocean world. Or maybe they'll discover that it's tectonically active today. "We need to find out," he says. "Because she's waiting to tell us something, and I would hate to miss the boat."

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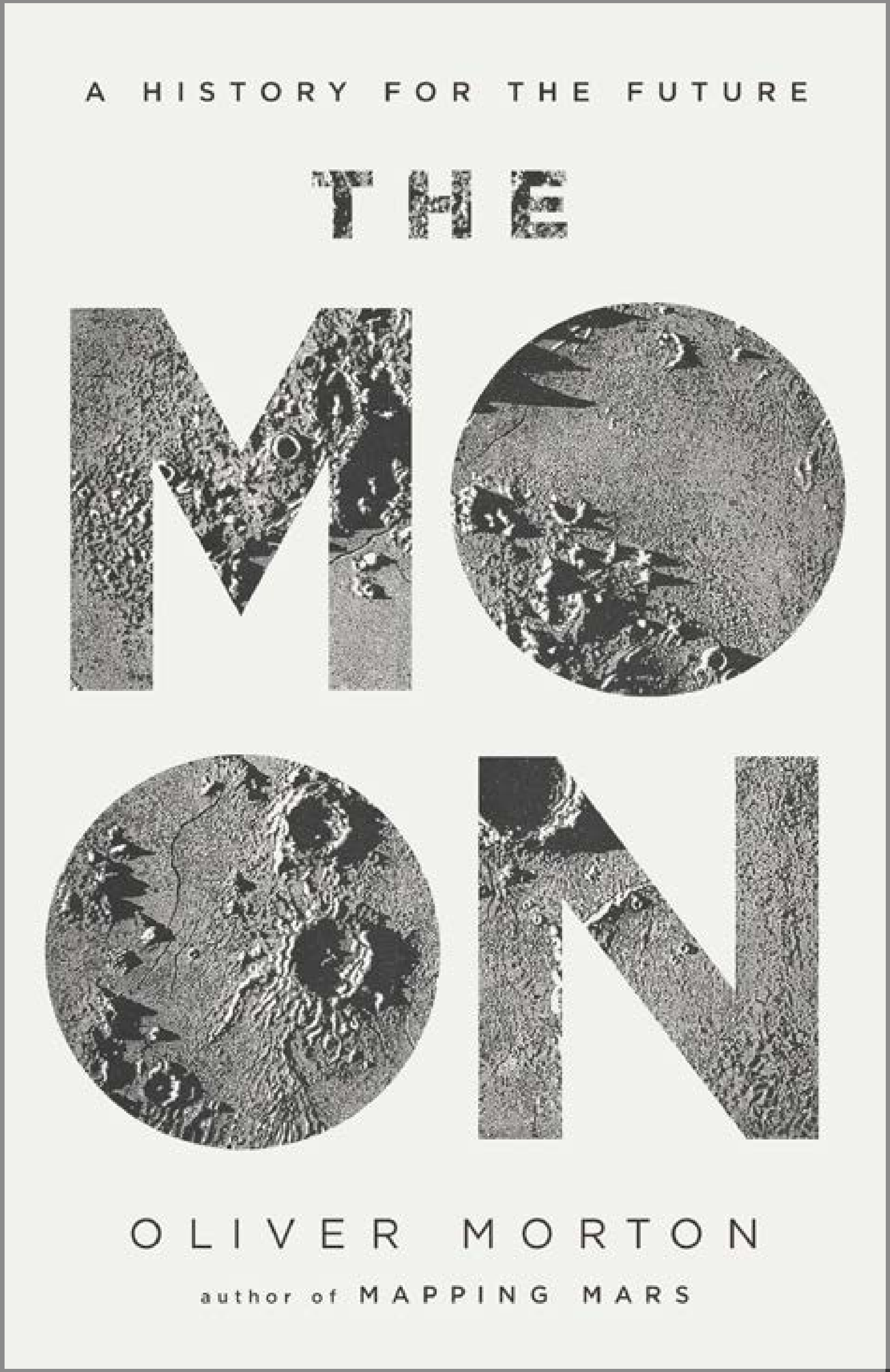
Q & A

The Once and Future Moon

Oliver Morton discusses his new book about how art, science and politics have shaped past, present and planned voyages to Earth's nearest celestial neighbor

By Lee Billings



ECONOMIST BOOKS

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

ON JULY 20, 2019, A HALF-CENTURY will have passed since *Apollo 11* astronauts Neil Armstrong and Edwin "Buzz" Aldrin became the first humans to walk on the moon. More than just an excuse to celebrate an epochal achievement, the 50th anniversary is also an opportunity to reflect on the Apollo program's complex origins and legacy—and on how lunar exploration in general has changed our understanding not only of the moon but also of Earth and ourselves.

To that end, a huge number of commemorative media and memorabilia are already appearing on screens and shelves around the world, with even more to follow in coming months. Of the books in this overwhelming flood, one stands out for the understated elegance of its prose and the profoundly wide-angle view it offers of its subject: Oliver Morton's *The Moon: A History for the Future*. Only one of the book's eight chapters is explicitly devoted to the Apollo missions, but the tome, in its entirety, places humanity's lunar forays into new, thought-provoking contexts guaranteed to surprise and delight even the most knowledgeable space buff.

Scientific American spoke with Morton, a writer and editor at the *Economist*, about the motivations for future lunar voyages, how to responsibly conduct them and why the moon should make us all reconsider what it means to live on Earth.

[*An edited transcript of the conversation follows.*]

Why write this book right now? Is it just the 50th anniversary of the first human lunar landing, or is it more than that?
It's two things. The 50th anniversary of *Apollo 11* is important, particularly for people like me in their mid-50s, because it's quite remarkable to realize that of all the things we thought back then about the extraordinary future, one thing we didn't think about was that by 1972 human journeys to the moon would be over and that no one would go back. But the other thing, of course, is that it's quite clear now that people are going to go back. I believe there are more people on Earth today who will walk on the moon than who have walked on the moon.

There are many proffered reasons for going back: doing interesting science or the possibility of using resources there. And of course, there's the matter of "great power" geopolitics and the symbolism involved in being there, overhead in the skies of everyone on Earth. I don't exactly applaud that, but I can see the reality of it. But when it comes down to it, the real reason for going back is that people in general have more power now, and getting to the moon is less difficult than it used to be. In the 1960s it took the supreme efforts of the world's preeminent superpower to put people on the moon. And that's just not the case anymore. The attitude is shifting from being "Why go to the moon?" to "Hey, why not?"

So it's worth thinking again about what it is that the moon means to people and what it could come to mean to people as we return.

Well, what does the moon mean to you? You discuss the spectrum of attitudes toward the moon a great deal in the book: Some people want the "sky moon"—just something to see in the sky. Others want the "rock moon," an object to be scientifically studied or mined for resources. Or "a moon that is at one with their Earth," a place one might routinely visit that, although exotic, is really not so out of this world. Which moon do you want?
I am somewhat confused about the moon. But I think what most fascinates me about the moon is its sheer unworldliness, the way it makes you think about [what] it is to be a world like Earth, and [what] the moon is deprived [of]. Thinking about the moon hard made me realize how extraordinary it is that on Earth, if you put something down, Earth will move it away from you—wind will blow it away, rain will wash it away. Eventually, a mountain range will rise up, or a sea will open, and that something will tumble down. On the moon—unless it's unhappy enough to be at ground zero for another asteroid strike—you put something down, and it stays down. Nothing much happens. The lack of anything on the moon really puts one's sense of what it is to be a "world" into question. A question that simply speculating

> **In the 1960s it took the supreme efforts of the world’s preeminent superpower to put people on the moon. And that’s just not the case anymore. The attitude is shifting from being “Why go to the moon?” to “Hey, why not?”**

about one’s feet on the moon, or about the moon becoming something other than a rock in the sky, doesn’t quite reach.

Earlier this year, Vice President Mike Pence announced NASA is going to somehow get U.S. astronauts back to the lunar surface by 2024. What do you think about that? Who do you think will be there next, and when and why?
What I think is that things are moving considerably faster than I would have expected when I began writing this book! I believe the next people to land on the moon will probably be American. Quite how they’ll do so, I’m not sure. It’s fairly unlikely that NASA will do it by 2024, as Pence suggested, partly because NASA has various handicaps in the “resource” sense of the word—it is carrying unnecessary weight in terms of being required to use a very large, very expensive, as yet unfinished NASA-developed booster, the Space Launch System, rather than alternatives such as SpaceX’s Falcon Heavy or perhaps the new rocket being developed by Jeff Bezos’s Blue Origin, the New Glenn. And I think that's a genuine problem for NASA, as well as this idea of building a little space station—the lunar Gateway—around the moon before going back down to the surface, which is not something that has a great deal of support outside of NASA and the contractors who are building this thing.

Meanwhile the Chinese seem to be planning to go, too, but they are in no rush. It would be a significant effort, and I think China sees human lunar landings as something that would just be “nice to have.” But China’s interest kind of forces America’s hand, in that there is a symbolism to being the first on the moon that is lost if someone else goes up there, and you’re not there, too. There’s a real aspect of “great power” rivalry here.

One thing I enjoyed about the book was your unflinching discussion of the profound social inequalities often associated with space exploration. You grapple with a perennial criticism of the Apollo program—that it was an overly expensive distraction from more pressing problems on Earth. And you write about how those missions and the prosperity that made them possible in the first place are inseparable products of historical injustices, from the obliteration of Native American populations to the slave trade.
Yes, it’s important to remember that Apollo was not universally popular, even among Americans, even at the time. I suppose the most famous example is Gil Scott-Heron’s song “Whitey on the Moon.” You know, “A rat done bit my sister Nell, with Whitey on the moon.” Hugely though I respect NASA’s astronauts of the 1960s and 1970s, they were all middle-aged white men, mostly from the officer class—that’s not “humanity” as the term is usually construed! One uncontestably interesting thing about a return to the moon is the opportunity it presents for more of “humanity”—women, people of color, people of developing nations, people of a wider range of ages, and so on—to actually go there.

And the idea that Apollo was a distraction from Earth is quite a strong one, particularly in the context of global ecological change, climate change especially. But being able to go into space helped alert people to those problems. At the same time, if all you can do with the moon is watch Earth heat up from a distance, that’s not so great. One could argue, and I might, that sending humans to the moon is still too expensive—but it’s a tiny fraction of what we spend on many other things, and what we should be spending on problems such as climate change. If I had to choose between spending really effectively on climate change or spending profligately on missions to the moon, well, I’d be hard-pressed to choose the moon. But I don’t think that’s really the choice the world is facing at the moment. I don’t think the costs of human missions to the moon and of dealing with climate change are remotely of the same scale.

Somewhat relatedly, then, do we need to be concerned about protecting the environment of the moon? If so, how?
I’d like people to plan and perform their lunar missions in ways that don’t leave behind a terrible amount of mess. At the same time, the amount of mess that humans could make on the moon, com-

Some scientists have called the moon "Earth's attic," because for billions of years, it has been collecting material ejected from our planet by impacts and other processes.

pared with the messes we can and do make on Earth, is always going to be absolutely trifling. For the time being, I'd certainly suggest that people avoid visiting the obvious heritage sites, such as the *Apollo 11* and *Apollo 17* landing locations.

The situation has become more complex since the days of Apollo, though, because there's now a strong consensus that interesting volatiles—water ice, in particular—are stored in shadowed craters at the moon's poles. That water ice could be used for, among other things, producing rocket fuel, which has many people excited. I'd like to see some discussion of an international agreement to cover the use of those potential resources, because right now, I don't believe there are any meaningful constraints on what anyone can do with them. I wouldn't want anything needlessly punitive, and we don't need every molecule of ice that's ever settled in a crater to be preserved as is. But the discussion is important, because we don't really know yet the extent of the water-ice deposits there, and we also don't know the trade-off between using them as a physical resource versus using them as a scientific resource. We have no real sense yet of what information from lunar and even earthly history is stored in those ices.

Speaking of science, what do you think would be the most compelling scientific reason to go to the moon now?

To me, the most compelling thing is the possibility of finding samples from the very early Earth on the moon. Some scientists have called the moon "Earth's attic," because for billions of years, it has been collecting material ejected from our planet by impacts and other processes. The arguments for all this remain somewhat theoretical, but there really should be quite a significant number of extremely old Earth rocks up there, on the lunar surface, from parts of our planet's history we can't otherwise directly study. Similarly, there might be a much smaller amount of rocks from early Venus there, from back when that world may have been much more Earth-like, which would be really fascinating to study. And frankly, it's much easier to gather up and sort through moon rocks by the ton than to retrieve any rocks at all from present-day Venus, the surface of which is very hard to get to and even harder to return from.

I also find something poetic and scientific about the notion of doing radio astronomy from the moon's far side, which, because it always faces away from Earth, is the only place within light-years where such observations could be unaffected by our planet's electromagnetic babble. There are radio-based studies of the early universe that, at the moment, scientists can only imagine performing from that vantage point. Most of my thinking about the moon involves using it to gaze back at, and better understand, Earth, so the idea that it could be a platform for looking farther out to the universe's beginnings is one that similarly pleases me.

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*.

The Unseen *Apollo 11*

Much of the treasure trove of *Apollo 11* images is rarely shown

By Caleb A. Scharf

IN THE 50 YEARS SINCE JULY 20, 1969, and the first humans landing on the moon, we've grown accustomed to seeing the same pictures of the *Apollo 11* mission again and again. But there is a wealth of material beautifully archived at NASA. In honor of Neil Armstrong, Edwin "Buzz" Aldrin and Michael Collins, as well as the thousands of people who contributed to this extraordinary—and provocative, moving, controversial, epoch-making, tear-jerking and outrageous—undertaking, here are a few selected images that don't often see the light of day—or space.

Lunar module after separation.

NASA

On July 12, 1969, *Apollo 11* astronauts Buzz Aldrin, Neil Armstrong and Michael Collins take their final press conference from inside their semi-isolated NASA quarters (done to minimize the odds of getting sick and to allow for a period of intense last-minute training). Deke Slayton is seen on the stool at the far left.

NASA

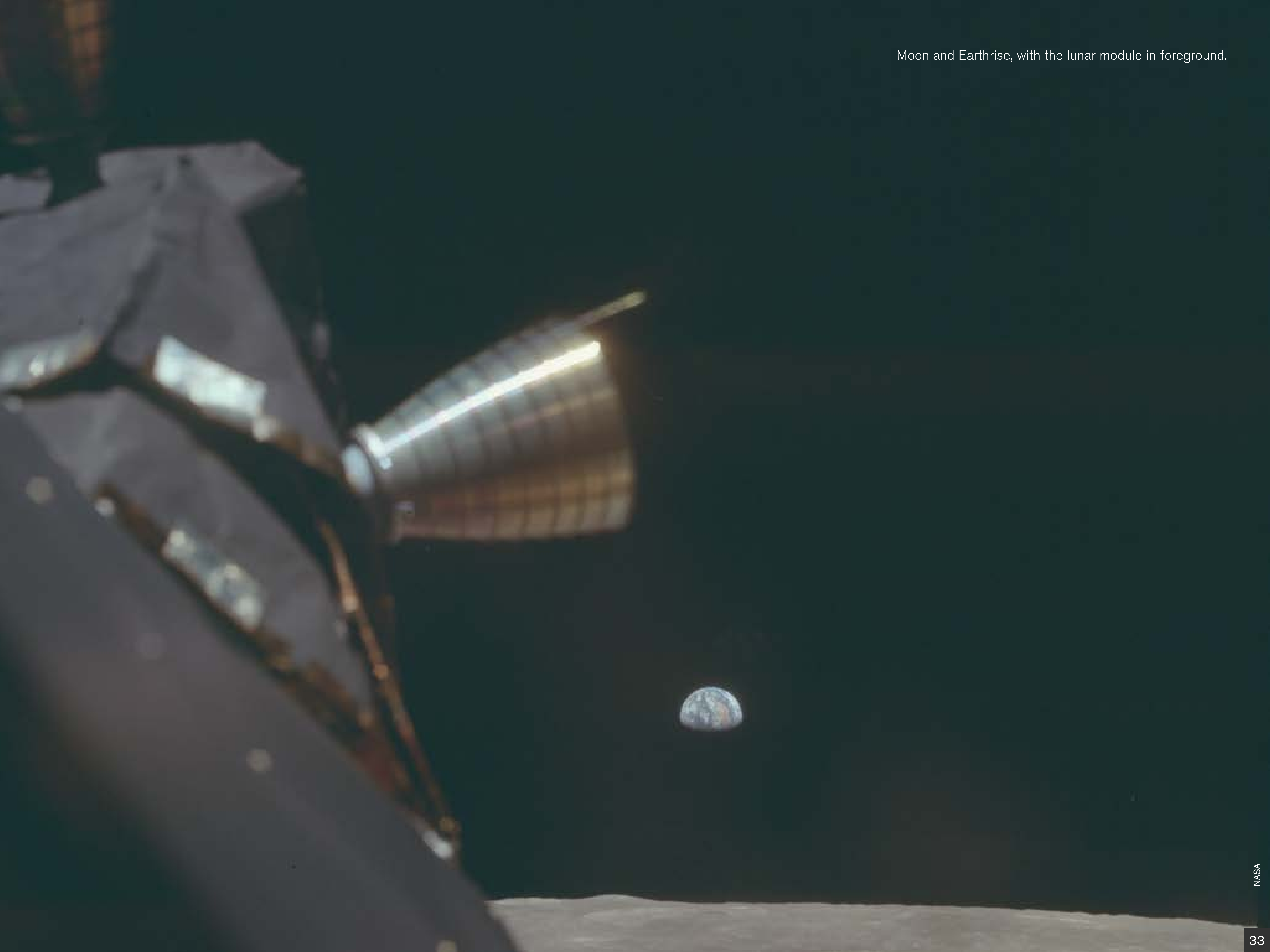
On the day of the launch, on July 16, 1969, Armstrong and Collins cross the walkway to the command module atop the Saturn V rocket. It will be an early-morning launch.

Saturn V launches, as seen from the Kennedy Space Center control room.

NASA (2)

Leaving Earth behind.

NASA



Moon and Earthrise, with the lunar module in foreground.

NASA

First image taken by Armstrong after setting foot on the moon.

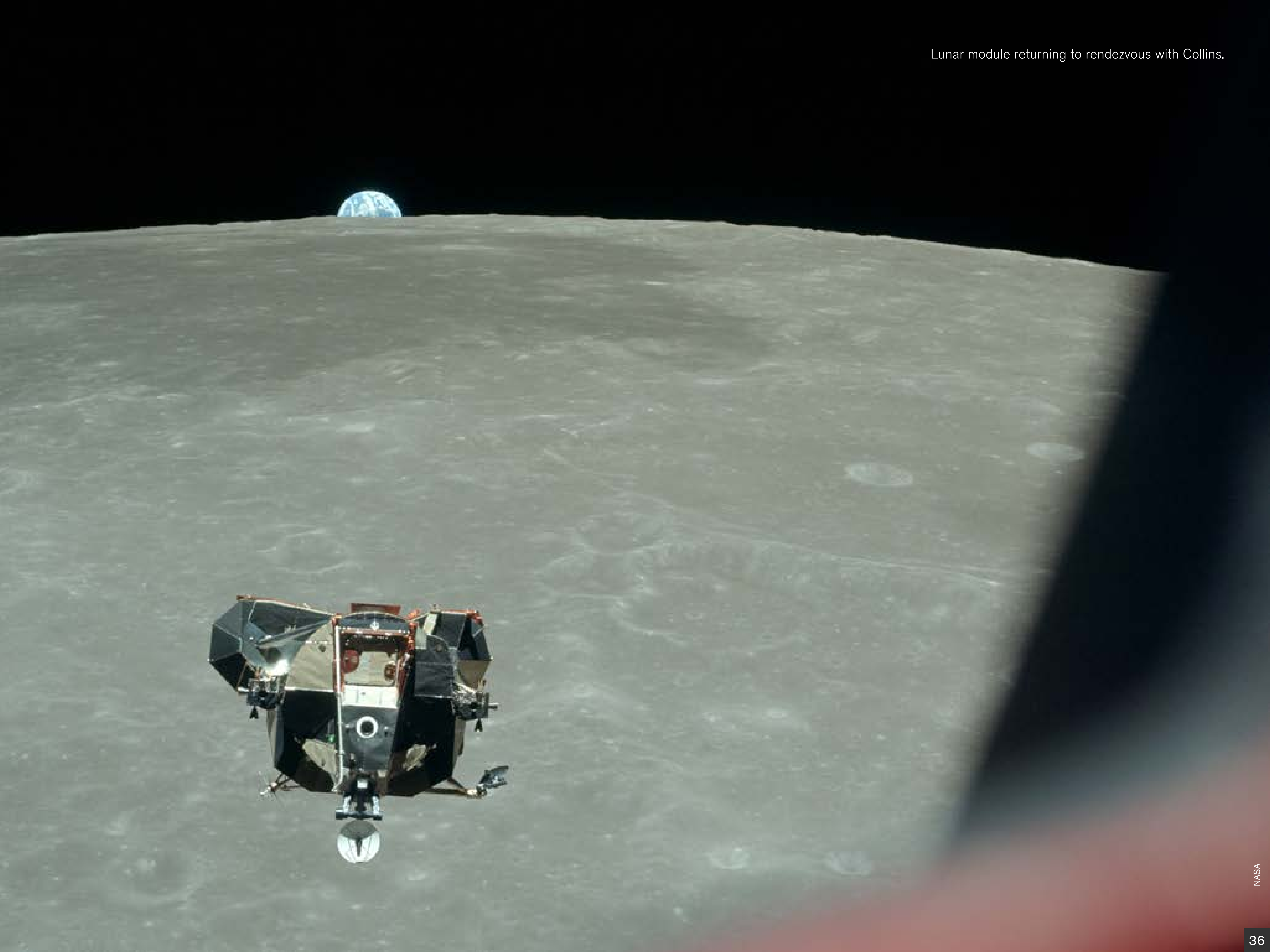
Plaque left on the moon.

NASA (2)

Aldrin moving to place some of the mission's experiments and devices.

NASA

Lunar module returning to rendezvous with Collins.



NASA

View of the moon after trans-Earth injection and the start of the astronauts' return to Earth.

NASA

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

PHYSICS

Spin-Swapping Particles Could Be "Quantum Cheshire Cats"

A proposed experiment to swap fundamental properties between photons carries profound implications for our understanding of reality itself

GETTY IMAGES

One of the most mind-bending revelations of quantum physics over the past century has been that properties of particles are possibly not real until they are measured. Now a new thought experiment suggests that conclusion may be too tame: it seems that particles' properties—their spin, for instance—may not even belong to them. This possibility is akin to saying that your personality does not belong to you.

The new study claims to demonstrate this paradoxical disconnect between particles and their properties via a new version of the so-called quantum Cheshire cat experiment. First performed in 2013, the experiment draws its name from the disappearing feline in Lewis Carroll's *Alice's Adventures in Wonderland* and involves the ostensible separation of a cat (actually, a particle) from its grin (some property of the particle).

The new version of the experiment starts with two grinning Cheshire cats and ends with the grin of one cat gracing the other cat's face, and vice versa. In quantum terminology, it shows how two particles could end up exchanging their properties, or physical attributes.

"Niels Bohr's view [was] that until you do a measurement on a quantum system, you cannot say that the physical attribute actually exists. That questions the reality of physical attributes," says Arun Kumar Pati of the Harish-Chandra Research Institute (HRI) in India, who co-authored the new work. "Our thought experiment takes that view a step ahead. Not only are the attributes not real, but they could not be yours. It questions the reality at a much deeper level."

THE WEAK VERSUS THE STRONG

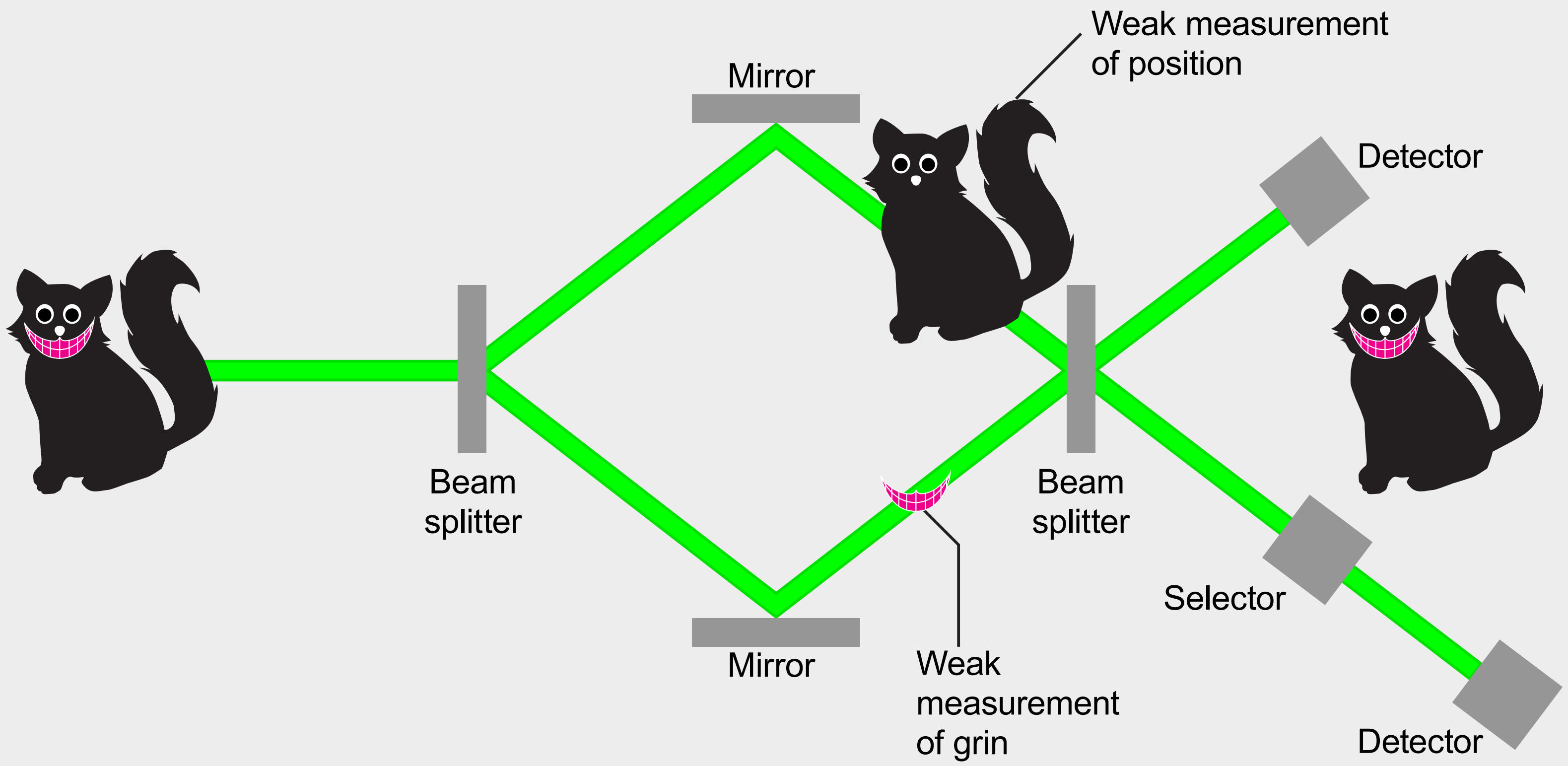
To arrive at their conclusion, Pati and his HRI colleague Debmalya Das resorted to a technique known as weak measurement.

In standard quantum mechanics, examining the state of a quantum system—such as a particle or an atom—involves a so-called strong measurement, which can be something as simple as a detector registering the arrival of a photon. A particle is first prepared in some initial state, a process called preselection. Then the quantum state of the particle evolves over time, under the influence of external forces, and it can end up in a superposition of many states. The strong measurement randomly "collapses" the superposition into one of those many possible states—a process that is unavoidably destructive. For example, if you were measuring the position of a photon, a strong measurement would locate the photon but also destroy the superposition.

Weak measurements, on the other hand, are not so heavy-handed. They represent an idea that goes back to 1988, to a theory devised by Yakir Aharonov, David Z. Albert and Lev Vaidman, all then at the University of South Carolina and Tel Aviv University. The trio asked, What if the measuring device

Creating a Quantum Cheshire Cat

Drawing its name from the disappearing feline in Lewis Carroll's *Alice's Adventures in Wonderland*, the quantum Cheshire cat experiment involves the separation of a "cat" (a particle) from its "grin" (some property of the particle). The canonical version of the experiment, first performed in 2013 and simplistically represented here, fired neutrons (a black cat) possessing a particular spin (a pink grin) through a system of optical elements including an interferometer, beam splitters, mirrors and detectors. A carefully choreographed sequence of strong and weak measurements upon the neutrons as they traversed the system yielded a paradoxical result, in which the neutrons passed through one of two paths while their spins were only observable in the other. In other words, the "cat" had been separated from its "grin."



MELISSA THOMAS BAUM, BUCKYBALL DESIGN; SOURCE: "OBSERVATION OF A QUANTUM CHESHIRE CAT IN A MATTER-WAVE INTERFEROMETER EXPERIMENT," BY TOBIAS DENKMAYR, ET AL, IN *NATURE COMMUNICATIONS*, VOL. 5, NO. 4492; JULY 29, 2014

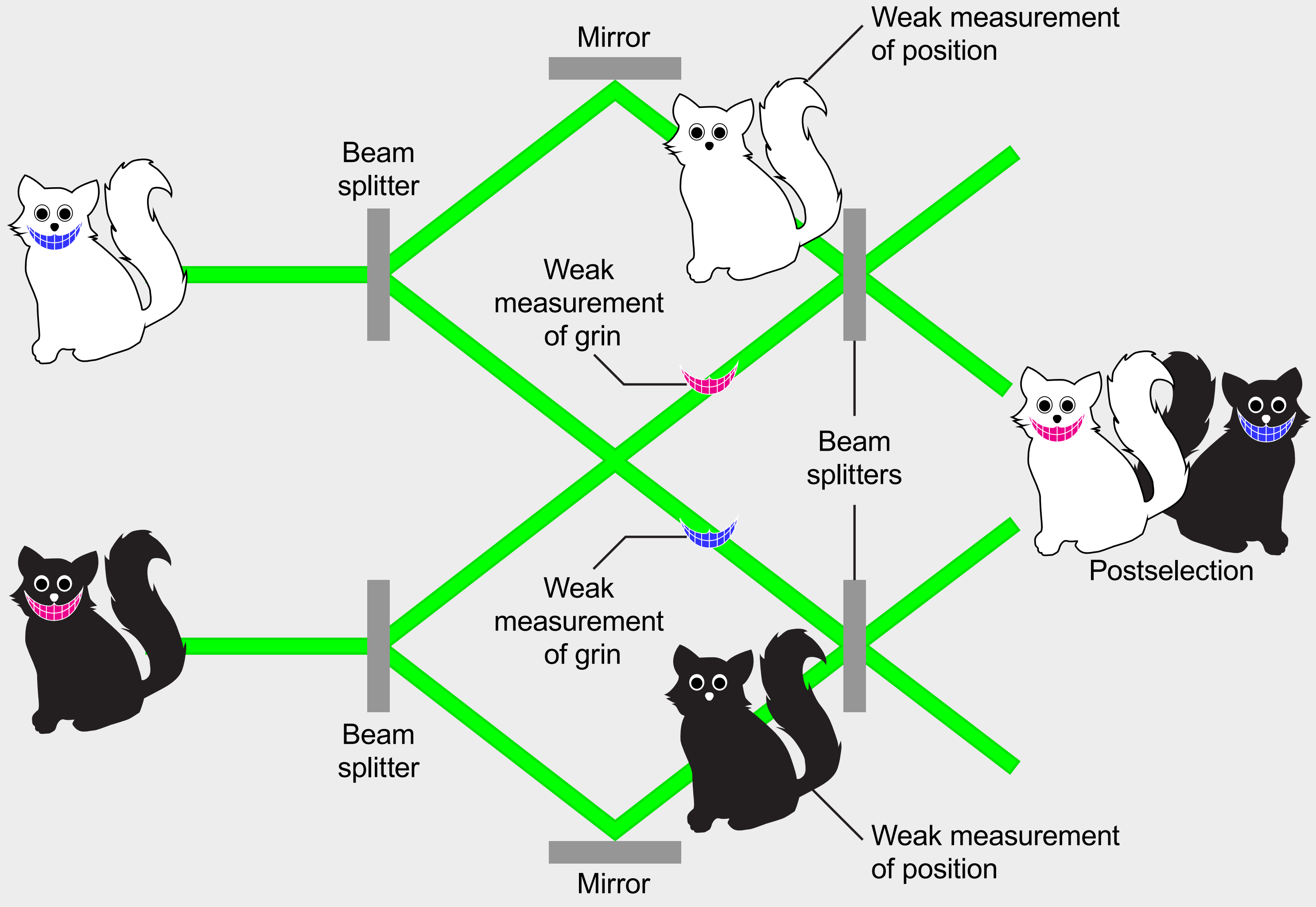
interacted extremely weakly with the particle? While such a measurement would not destroy the quantum state (and thus the state would continue evolving), it would result in a value for the state with a very large uncertainty. If you performed the measurements over and over again, with an ensemble of identically prepared, or preselected, particles, then you would get a distribution of weak measurement values.

On its own, this distribution is not informative. But add one more stage to the process, and things get very interesting. After each weak measurement, you let the particle evolve and then perform a strong, destructive measurement on it. Repeat this action for every identically preselected, weakly measured particle. Each strong measurement will give a different value because of the random collapse of the superposition. Now select only those particles whose final positions have a certain value—doing so is called postselection. Then discard information about all of the particles that do not end up in this postselected stage. What Aharonov and his colleagues argued is that you can now take the weakly measured values for the subset of postselected particles and turn it into a "weak value" that tells you something about a property of the particles, such as their spin in a given direction.

An intriguing outcome of this approach to quantum systems has to do with the nature of time. According to the mathematics developed by Aharonov and his colleagues, weak values are influenced by both the initial preselected quantum state (the past) and the final postselected quantum

Two Quantum Cats Swap Grins

A newly proposed elaboration of the quantum Cheshire cat experiment calls for not only separating particles from their properties but also exchanging those properties between the particles. In other words, this version of the experiment would first strip away and then swap the grins of two quantum Cheshire cats. In this experiment, which crucially relies on intermixing the outputs of not one but two interferometers before performing multiple strong and weak measurements, two photons (the white and the black cats) are decoupled from their polarizations (the blue and the pink grins). This illustration depicts the paths of the photons and their weakly measured polarizations through a schematic representation of the proposed optical system. The experiment's final result, its creators say, would be the exchange of polarization states and formation of a single entangled state between the two spatially separated photons.



MELISSA THOMAS BAUM *BUCKYBALL DESIGN*; SOURCE: "CAN TWO QUANTUM CHESHIRE CATS EXCHANGE GRINS?" BY DEBMALYA DAS ET AL., IN ARXIV:1904.07707; APRIL 14, 2019 state (the future). Time, in this way of thinking, flows both ways: the future influences the present.

WHOSE PROPERTY IS IT, ANYWAY?

In a first-of-its-kind experiment conducted in 2013 and published in 2014, Tobias Denkmayr of the Technical University of Vienna, Jeff Tollaksen of Chapman University and their colleagues used weak measurements to separate the quantum Cheshire cat from its grin.

In their experiment, preselected neutrons with a particular spin were sent, one by one, into a beam splitter, which is a device that splits a beam of particles into two. Each incoming neutron ended up in a superposition of two states: taking paths A and B. These two paths were recombined in a so-called interferometer, which caused the quantum states to interfere. The neutrons then headed toward output detectors. In one of the output paths of the interferometer, the experiment involved a strong measurement of a particular spin state of the neutrons. Neutrons that satisfied this criterion were considered to be postselected. The experimenters discarded all of the other neutrons for their analysis.

For these postselected particles, the team also performed two sets of weak measurements: one for the position of the particles, and the other for their spin. These dual measurements suggested that the particles were going through path B, while the weak value of their spin could only be measured in path A. The cat had been separated from its grin.

"From the old perspective of preparing a particle and then doing a strong measurement, it is impossible to separate a particle from its properties," says Tollaksen, who wrote about the Cheshire cat paradox in his 2001 Ph.D. thesis.

Now Pati and Das have extended the Cheshire cat experiment to their thought experiment, which not only separates a particle from its properties but also causes one particle to take on a property previously associated with another, and vice versa.

The thought experiment involves putting two interferometers side by side, such that each particle first encounters a beam splitter. After going through the beam splitter, the particle enters into a superposition of two states: taking the left and right paths.

Then comes a twist: The alignment of the setup is such that interferometer 1's right path, which would normally be recombined with its corresponding left path, is instead recombined with interferometer 2's right path. And the interferometers' left paths are recombined as well. When recombined, the various quantum states interfere with one another. Then the two outputs from each interferometer encounter a series of beam splitters and detectors. These beam splitters are designed to make photons with one type of polarization go one way and the rest go the other way. (Polarization describes the orientation of a photon's vibrating electric and magnetic fields.) The postselection involves choosing only those photons that cause a particular set of six detectors to click simultaneously. All other photons are discarded.

According to Pati and Das, if one were to calculate weak values for the position and polarization of each pair of photons in the postselected ensemble, then the weak values would show that photon 1 went through the left arm of interferometer 1, whereas its polarization appeared in the left arm of interferometer 2. Similarly, photon 2 would appear in the right arm of interferometer 2, whereas its polarization would show up in the right arm of interferometer 1. At least, that is how the researchers interpret the weak values.

This interpretation of the thought experiment suggests that after the particles and their properties are decoupled, and their paths are recombined and finally subjected to strong measurements, photon 1 ends up with the polarization of photon 2, and vice versa. The cats and their grins are first separated, and then the cats exchange grins. Also, the photons, despite being separated from their initial properties, all end up in one massive entangled state—meaning that they can only be described by a single global quantum state.

"It doesn't surprise me," says Tollaksen, who is used to the seeming paradoxes thrown up by weak measurements. But "it's very good work."

A DISAGREEMENT OVER DETAILS

Experimentalist Aephraim Steinberg of the University of Toronto is also not surprised but for different reasons. He points out that an interaction between particles results in those particles getting entangled (as happens in Pati and Das's thought experiment), and this entanglement can lead to the particles swapping properties. Such swapping is the basis of a so-called SWAP gate, a well-studied operation used in quantum computing, Steinberg says. “It would indeed be interesting if they could swap their polarizations without ever interacting,” he adds.

But Steinberg is more surprised, even concerned, by the new experiment’s design. “It relies on two photons traversing a set of interferometers and then causing six different detectors to fire simultaneously. This is, of course, impossible,” he says. “The authors seem to be imagining one detector sensitive to where a photon is, while another detector (at another location) could simultaneously measure the photon’s polarization. In this sense, they seem to be trying to “build in” the separation of the photon’s different properties from the start rather than devising an experiment to reveal it.”

Tollaksen also says that having six detectors firing simultaneously with only two photons is simply not possible. But he thinks Pati and Das’s conceptual idea is sound. “As far as I can tell, it seems to me that even the requirement of all six [detectors] could be boiled back down to two with the right optics and still produce the right post-selection,” he says. “If so, the fundamental swapping idea they are playing with might be salvageable.”

But Pati says that his and Das’s experiment should work as designed—and with existing technology, too. “The detector clicks are for various degrees of freedom or attributes of the two photons,” he says, thus allowing for six simultaneous detections.

There is also a bigger issue of whether the weak values obtained via weak measurements are telling us something about what is real. “In general, I think too much is made of the quantum Cheshire cat being a paradox,” says theorist Michael Hall of the Australian National University. “Weak values are not the outcomes of individual measurements in general. They are only average values of many repeated measurements.” Hall argues that such average values cannot be accorded the same status as the outcome of individual strong measurements.

Nevertheless, weak measurements are already being used for seemingly impossible applications. For example, if one selects the initial state and the postselected state of particles such that there is very little overlap between the two, then the percentage of particles that have to be thrown away because they are not postselected becomes very large. But for the very few that remain, the weak values can be extremely useful. John C. Howell of the University of Rochester and his colleagues have already used such weak values to measure displacements of about 14 femtometers, which is roughly the size of a uranium nucleus.

Concerns about Pati and Das’s thought experiment notwithstanding, the debate over the meaning of weak values is also one over the correct theory for describing the quantum world, particularly the role of time. “You need to start thinking about the relevance of the future on the present. The property [of a particle] at any given moment of time is influenced by the future,” Tollaksen says. “When you shift your thinking to that, then all of these things, like the Cheshire cat, are not at all surprising.”

Bjørn Ekeberg is a philosopher of science and author of *Metaphysical Experiments*, published by University of Minnesota Press.

OBSERVATIONS

Cosmology Has Some Big Problems

The field relies on a conceptual framework that has trouble accounting for new observations

THANAPOL SISRANG *GETTY IMAGES*

What do we really know about our universe? Born out of a cosmic explosion 13.8 billion years ago, the universe rapidly inflated and then cooled. It is still expanding at an increasing rate and is mostly made up of unknown dark matter and dark energy ... right?

This well-known story is usually taken as a self-evident scientific fact, despite the relative lack of empirical evidence—and despite a steady crop of discrepancies arising with observations of the distant universe.

In recent months, new measurements of the Hubble constant—the rate of universal expansion—suggested major differences between two independent methods of calculation. Discrepancies on the expansion rate have huge implications not simply for calculation but for the validity of cosmology's current Standard Model at the extreme scales of the cosmos.

Another recent probe found galaxies inconsistent with the theory of dark matter, which posits this hypothetical substance to be everywhere. But according to the latest measurements, it is not, suggesting the theory needs to be reexamined.

It's perhaps worth stopping to ask why astrophysicists hypothesize dark matter to be everywhere in the universe. The answer lies in a peculiar feature of cosmological physics that is not often remarked on. A crucial function of theories such as dark matter, dark energy and inflation—each in its own way tied to the big bang paradigm—is not to describe known empirical phenomena but rather to maintain the mathematical coherence of the framework itself while accounting for discrepant observations. Fundamentally, they are names for something that must exist insofar as the framework is assumed to be universally valid.

Each new discrepancy between observation and theory can, of course, in and of itself be considered an exciting promise of more research, a progressive refinement toward the truth. But when they add up, they could also suggest a more confounding problem that is not resolved by tweaking parameters or adding new variables.

Consider the context of the problem and its history. As a mathematically driven science, cosmological physics is usually thought to be extremely precise. But the cosmos is unlike any scientific subject matter on earth. A theory of the entire universe, based on our own tiny neighborhood as the only known sample of it, requires a lot of simplifying assumptions. When these assumptions are multiplied and stretched across vast distances, the potential for error increases, and this is further compounded by our very limited means of testing.

Historically, Newton's physical laws made up a theoretical framework that worked for our own solar system with remarkable precision. Both Uranus and Neptune, for example, were discovered through predictions based on Newton's model. But as the scales grew larger, its validity proved limited. Einstein's general relativity framework provided an extended and more precise reach beyond the farthest reaches of our own galaxy. But just how far could it go?

The big bang paradigm that emerged in the mid-20th century effectively stretches the model's validity to a kind of infinity, defined either as the boundary of the radius of the universe (calculated at 46 billion light-years) or in terms of the beginning of time. This giant stretch is based on a few concrete discoveries, such as Edwin Hubble's observation that the universe appears to be expanding (in 1929) and the detection of microwave background radiation (in 1964). But considering the scale involved, these limited observations have had an outsized influence on cosmological theory.

It is, of course, entirely plausible that the validity of general relativity breaks down much closer to our own home than at the edge of the hypothetical end of the universe. And if that were the case, today's multilayered theoretical edifice of the big bang paradigm would turn out to be a confusing mix of fictional beasts invented to uphold the model, along with empirically valid variables mutually reliant on each other to the point of making it impossible to sort science from fiction.

Compounding this problem, most observations of the universe occur experimentally and indirectly. Today's space telescopes provide no direct view of anything—they produce measurements through an interplay of theoretical predictions and pliable parameters, in which the model is involved every step of the way. The framework literally frames the problem; it determines where and how to observe. And so, despite the advanced technologies and methods involved, the profound limitations to the endeavor also increase the risk of being led astray by the kind of assumptions that cannot be calculated.

After spending many years researching the foundations of cosmological physics from a philosophy of science perspective, I have not been surprised to hear some scientists openly talking about a crisis in cosmology. In the big "inflation debate" in *Scientific American* a few years ago, a key piece of the big bang paradigm was criticized by one of the theory's original proponents for having become indefensible as a scientific theory.

Why? Because inflation theory relies on ad hoc contrivances to accommodate almost any data, and because its proposed physical field is not based on anything with empirical justification. This is probably because a crucial function of inflation is to bridge the transition from an unknowable big bang to a physics we can recognize today. So, is it science or a convenient invention?

A few astrophysicists, such as Michael J. Disney, have criticized the big bang paradigm for its lack of demonstrated certainties. In his analysis, the theoretical framework has far fewer certain observations than free parameters to tweak them—a so-called negative significance that would be an alarming sign for any science. As Disney writes in *American Scientist*: "A skeptic is entitled to feel that a negative significance, after so much time, effort and trimming, is nothing more than one would expect of a folktale constantly re-edited to fit inconvenient new observations."

As I discuss in my new book, *Metaphysical Experiments*, there is a deeper history behind the current problems. The big bang hypothesis itself originally emerged as an indirect consequence of general relativity undergoing remodeling. Einstein had made a fundamental assumption about the universe, that it was static in both space and time, and to make his equations add up, he added a "cosmological constant," for which he freely admitted there was no physical justification.

But when Hubble observed that the universe was expanding and Einstein's solution no longer seemed to make sense, some mathematical physicists tried to change a fundamental assumption of the model: that the universe was the same in all spatial directions but variant in time. Not insignificantly, this theory came with a very promising upside: a possible merger between cosmology and nuclear physics. Could the brave new model of the atom also explain our universe?

From the outset, the theory only spoke to the immediate aftermath of an explicitly hypothetical event, whose principal function was as a limit condition, the point at which the theory breaks down. Big bang theory says nothing about the big bang; it is rather a possible hypothetical premise for resolving general relativity.

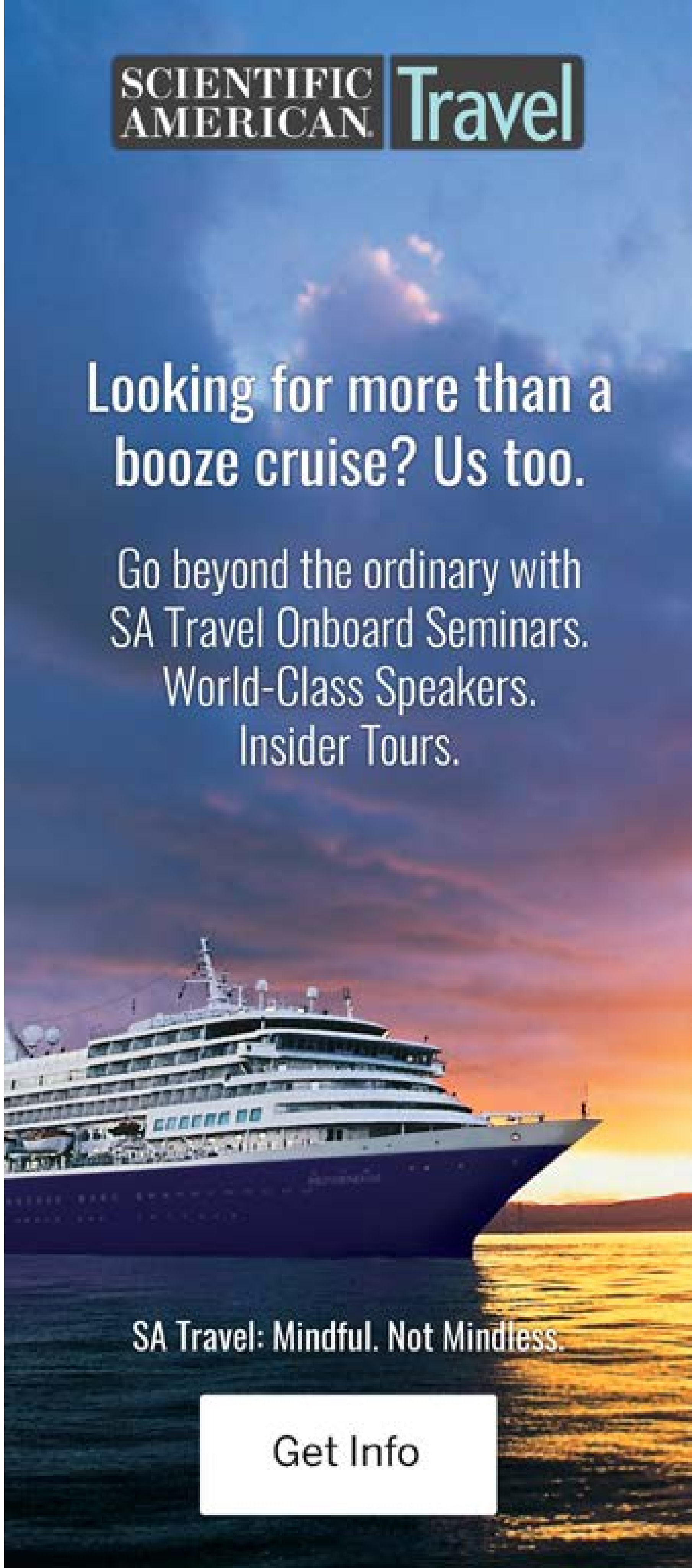
On top of this undemonstrable but very productive hypothesis, floor on floor has been added intact, with vastly extended scales and new discrepancies. To explain observations of galaxies inconsistent with general relativity, the existence of dark matter was posited as an unknown and invisible form of matter calculated to make up more than a quarter of all mass-energy content in the universe—assuming, of course, the framework is universally valid. In 1998, when a set of supernova measurements of accelerating galaxies seemed at odds with the framework, a new theory emerged of a mysterious force called dark energy, calculated to fill circa 70 percent of the mass-energy of the universe.

The crux of today's cosmological paradigm is that in order to maintain a mathematically unified theory valid for the entire universe, we must accept that 95 percent of our cosmos is furnished by completely unknown elements and forces for which we have no empirical evidence whatsoever. For a scientist to be confident of this picture requires an exceptional faith in the power of mathematical unification.

In the end, the conundrum for cosmology is its reliance on the framework as a necessary presupposition for conducting research. For lack of a clear alternative, as astrophysicist Disney also notes, it is in a sense stuck with the paradigm. It seems more pragmatic to add new theoretical floors than to rethink the fundamentals.

Contrary to the scientific ideal of getting progressively closer to the truth, it looks rather like cosmology, to borrow a term from technology studies, has become path-dependent: overdetermined by the implications of its past inventions.

This article is based on edited excerpts from the book Metaphysical Experiments: Physics and the Invention of the Universe*, published by University of Minnesota Press.*



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OBSERVATIONS

Which Should Come First in Physics: Theory or Experiment?

Plans for giant particle accelerators of the future focus attention on how scientific discoveries are really made


GETTY IMAGES

The discovery of the Higgs particle at the Large Hadron Collider (LHC) over half a decade ago marked a milestone in the long journey toward understanding the deeper structure of matter. Today, particle physics strives to push a diverse range of experimental approaches from which we may glean new answers to fundamental questions regarding the creation of the universe and the nature of the mysterious and elusive dark matter.

Such an endeavor requires a post-LHC particle collider with an energy capability significantly greater than that of previous colliders. This is how the idea for the Future Circular Collider (FCC) at CERN came to be—a machine that could put the exploration of new physics in high gear. To understand the validity of this proposal, we should, however, start at the beginning and once more ask ourselves: How does physics progress?

Many believe that grand revolutions are driven exclusively by new theories, whereas experiments play the parts of movie extras. The played-out story goes a little something like this: theorists form conjectures, and experiments are used solely for the purposes of testing them. After all, most of us proclaim our admiration for Einstein's relativity or for quantum mechanics, but seldom do we pause and consider whether these awe-inspiring theories could have been attained without the contributions of the Michelson-Morley, Stern-Gerlach or black-body radiation experiments.

This simplistic picture, despite being far removed from the creative, and often surprising, ways in which physics has developed over time, remains quite widespread even among scientists. Its pernicious influence can be seen in the discussion of future facilities like the proposed FCC at CERN.

In the wake of the discovery of the Higgs boson in 2012, we finally have all of the puzzle pieces of the Standard Model (SM) of physics in place. Nevertheless, the unknowns regarding dark matter, neutrino masses, and the observed imbalance between matter and antimatter are among numerous indications that the SM is not the ultimate theory of elementary particles and their interactions.

Quite a number of theories have been developed to overcome the problems surrounding the SM, but so far none has been experimentally verified. This fact has left the world of physics brimming with anticipation. In the end, science has shown time and again that it can find new, creative ways to surmount any obstacles placed along its path. And one such way is for experimentation to assume the leading role, so that it can help get the stuck wagon of particle physics moving and out of the mire.

In this regard, the FCC study was launched by CERN in 2013 as a global effort for explaining different scenarios for particle colliders that could inaugurate the post-LHC era and for advancing key technologies. A staged approach, it entails the construction of an electron-positron collider followed by a proton collider, which would present an eightfold energy leap compared to the LHC and thus grant us direct access to a previously unexplored regime. Both colliders will be housed in a new 100-kilometer circumference tunnel. The FCC study complements previous design studies for linear colliders in Europe and Japan, while China also has similar plans for a large-scale circular collider.

Future colliders could offer a deep understanding of the Higgs properties, but even more important, they represent an opportunity for exploring uncharted territory in an unprecedented energy scale. As Gian Giudice, head of CERN's theoretical physics department, argues: "High-energy colliders remain an indispensable and irreplaceable tool to continue our exploration of the inner workings of the universe."

Nevertheless, the FCC is seen by some as a questionable scientific investment in the absence of clear theoretical guidance about where the elusive new physics may lie. The history of physics, however, offers evidence in support of a different view: that experiments often play a leading and exploratory role in the progress of science.

As the eminent historian of physics Peter Galison puts it, we have to "step down from the aristocratic view of physics that treats the discipline as if all interesting questions are structured by high theory." Besides, quite a few experiments have been realized without being guided by a well-established theory but were instead undertaken for the purposes of exploring new domains. Let us examine some illuminating examples.

In the 16th century, King Frederick II of Denmark financed Uraniborg, an early research center, where Tycho Brahe constructed large astronomical instruments, like a huge mural quadrant (unfortunately, the telescope was invented a few years later) and carried out many detailed observations that had not previously been possible. The realization of an enormous experimental structure, at a hitherto unprecedented scale, transformed our view of the world. Tycho Brahe's precise astronomical measurements enabled Johannes Kepler to develop his laws of planetary motion and to make a significant contribution to the scientific revolution.

The development of electromagnetism serves as another apt example: many electrical phenomena were discovered by physicists such as Charles Dufay, André-Marie Ampère and Michael Faraday in the 18th and 19th centuries through experiments that had not been guided by any developed theory of electricity.

Moving closer to the present day, we see that the entire history of particle physics is indeed full of similar cases. In the aftermath of World War II, a constant and laborious experimental effort characterized the field of particle physics, and it was what allowed the Standard Model to emerge through a "zoo" of newly discovered particles. As a prominent example, quarks, the fundamental constituents of the proton and neutron, were discovered through a number of exploratory experiments during the late 1960s at the Stanford Linear Accelerator.

The majority of practicing physicists recognize the exceptional importance of experiment as an exploratory process. For instance, Victor "Viki" Weisskopf, the former director-general of CERN and an icon of modern physics, grasped clearly the dynamics of the experimental process in the context of particle physics:

"There are three kinds of physicists, namely the machine builders, the experimental physicists, and the theoretical physicists. If we compare those three classes, we find that the machine builders are the most important ones, because if they were not there, we would not get into this small-scale region of space. If we compare this with the discovery of America, the machine builders correspond to captains and ship builders who truly developed the techniques at that time. The experimentalists were those fellows on the ships who sailed to the other side of the world and then jumped on the new islands and wrote down what they saw. The theoretical physicists are those fellows who stayed behind in Madrid and told Columbus that he was going to land in India." (Weisskopf 1977)

Despite being a theoretical physicist himself, he was able to recognize the exploratory character of experimentation in particle physics. Thus, his words eerily foreshadow the present era. As one of the most respected theoretical physicists of our time, Nima Arkani-Hamed, claimed in a recent interview, "when theorists are more confused, it's the time for more, not fewer experiments."

The FCC, at present, strives to keep alive the exploratory spirit of the previous fabled colliders. It is not intended to be used as a verification tool for a specific theory but as a means of paving multiple experimental paths for the future. The experimental process should be allowed to develop its own momentum. This does not mean that experimentation and instrumentation should not maintain a close relationship with the theoretical community; at the end of the day, there is but one physics, and it must ensure its unity.

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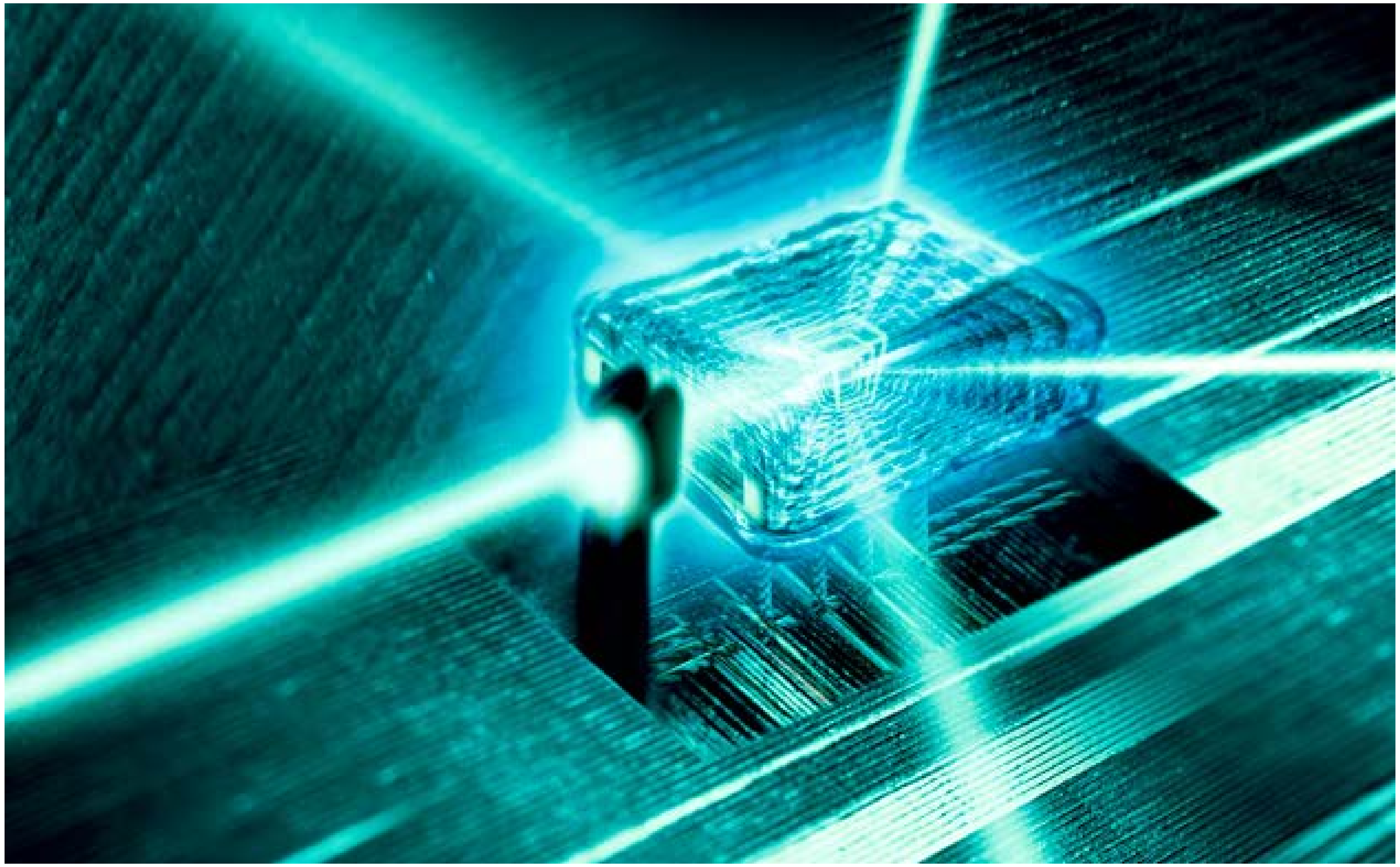
OBSERVATIONS

The Problem with Quantum Computers

It's called decoherence—but while a breakthrough solution seems years away, there are ways of getting around it

By now, most people have heard that quantum computing is a revolutionary technology that leverages the bizarre characteristics of quantum mechanics to solve certain problems faster than regular computers can. Those problems range from the worlds of mathematics to retail business and from physics to finance. If we get quantum technology right, the benefits should lift the entire economy and enhance U.S. competitiveness.

The promise of quantum computing was first recognized in the 1980s yet remains unfulfilled. Quantum computers are exceedingly difficult to engineer, build and program. As a result, they are crippled by errors in the form of noise, faults and loss of quantum coherence, which is crucial to their operation and yet falls apart before any nontrivial program has a chance to run to completion.



RICHARD KAIL *GETTY IMAGES*

This loss of coherence (called decoherence), caused by vibrations, temperature fluctuations, electromagnetic waves and other interactions with the outside environment, ultimately destroys the exotic quantum properties of the computer. Given the current pervasiveness of decoherence and other errors, contemporary quantum computers are unlikely to return correct answers for programs of even modest execution time.

While competing technologies and competing architectures are attacking these problems, no existing hardware platform can maintain coherence and provide the robust error correction required for large-scale computation. A breakthrough is probably several years away.

The billion-dollar question in the meantime is, how do we get useful results out of a computer that becomes unusably unreliable before completing a typical computation?

Answers are coming from intense investigation across a number of fronts, with researchers in industry, academia and the national laboratories pursuing a variety of methods for reducing errors. One approach is to guess what an error-free computation would look like based on the results of computations with various noise levels. A completely different approach, hybrid quantum-classical algorithms, runs only the most performance-critical sections of a program on a quantum computer, with the bulk of the program running on a more robust classical computer. These strategies and others are proving to be useful for dealing with the noisy environment of today's quantum computers.

While classical computers are also affected by various sources of errors, these errors can be corrected with a modest amount of extra storage and logic. Quantum error-correction schemes do exist but consume such a large number of qubits (quantum bits) that relatively few qubits remain for actual computation. That reduces the size of the computing task to a tiny fraction of what could run on defect-free hardware.

To put in perspective the importance of being stingy with qubit consumption, today's state-of-the-art, gate-based quantum computers, which use logic gates analogous to those forming the digital circuits found in the computer, smartphone or tablet you're reading this article on, boast a mere 50 qubits. That is just a mere fraction of the number of classical bits your device has available to it, typically hundreds of billions.

TAMING DEFECTS TO GET SOMETHING DONE

The trouble is, quantum mechanics challenges our intuition. So we struggle to figure out the best algorithms for performing meaningful tasks. To help overcome these problems, our team at Los Alamos National Laboratory is developing a method to invent and optimize algorithms that perform useful tasks on noisy quantum computers.

Algorithms are the lists of operations that tell a computer to do something, analogous to a cooking recipe. Compared to classical algorithms, the quantum kind are best kept as short as possible and, we have found, best tailored to the particular defects and noise regime of a given hardware device. That enables the algorithm to execute more processing steps within the constrained time frame before decoherence reduces the likelihood of a correct result to nearly zero.

In our interdisciplinary work on quantum computing at Los Alamos, funded by the Laboratory Directed Research and Development program, we are pursuing a key step in getting algorithms to run effectively. The main idea is to reduce the number of gates in an attempt to finish execution before decoherence and other sources of errors have a chance to unacceptably reduce the likelihood of success.

We use machine learning to translate, or compile, a quantum circuit into an optimally short equivalent that is specific to a particular quantum computer. Until recently, we have employed machine-learning methods on classical computers to search for shortened versions of quantum programs. Now, in a recent breakthrough, we have devised an approach that uses currently available quantum computers to compile their own quantum algorithms. That will avoid the massive computational overhead required to simulate quantum dynamics on classical computers.

Because this approach yields shorter algorithms than the state of the art, they consequently reduce the effects of noise. This machine-learning approach can also compensate for errors in a manner specific to the algorithm and hardware platform. It might find, for instance, that one qubit is less noisy than another, so the algorithm preferentially uses better qubits. In that situation, the machine learning creates a general algorithm to compute the assigned task on that computer using the fewest computational resources and the fewest logic gates. Thus optimized, the algorithm can run longer.

This method, which has worked in a limited setting on quantum computers now available to the public on the cloud, also takes advantage of quantum computers' superior ability to scaleup algorithms for large problems on the larger quantum computers envisioned for the future.

New work with quantum algorithms will give both experts and nonexperts the tools to perform calculations on a quantum computer. Application developers can begin to take advantage of quantum computing's potential for accelerating execution speed beyond the limits of conventional computing. These advances may bring us all several steps closer to having robust, reliable large-scale quantum computers to solve complex real-world problems that bring even the fastest classical computers to their knees.

Celestial Movement

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

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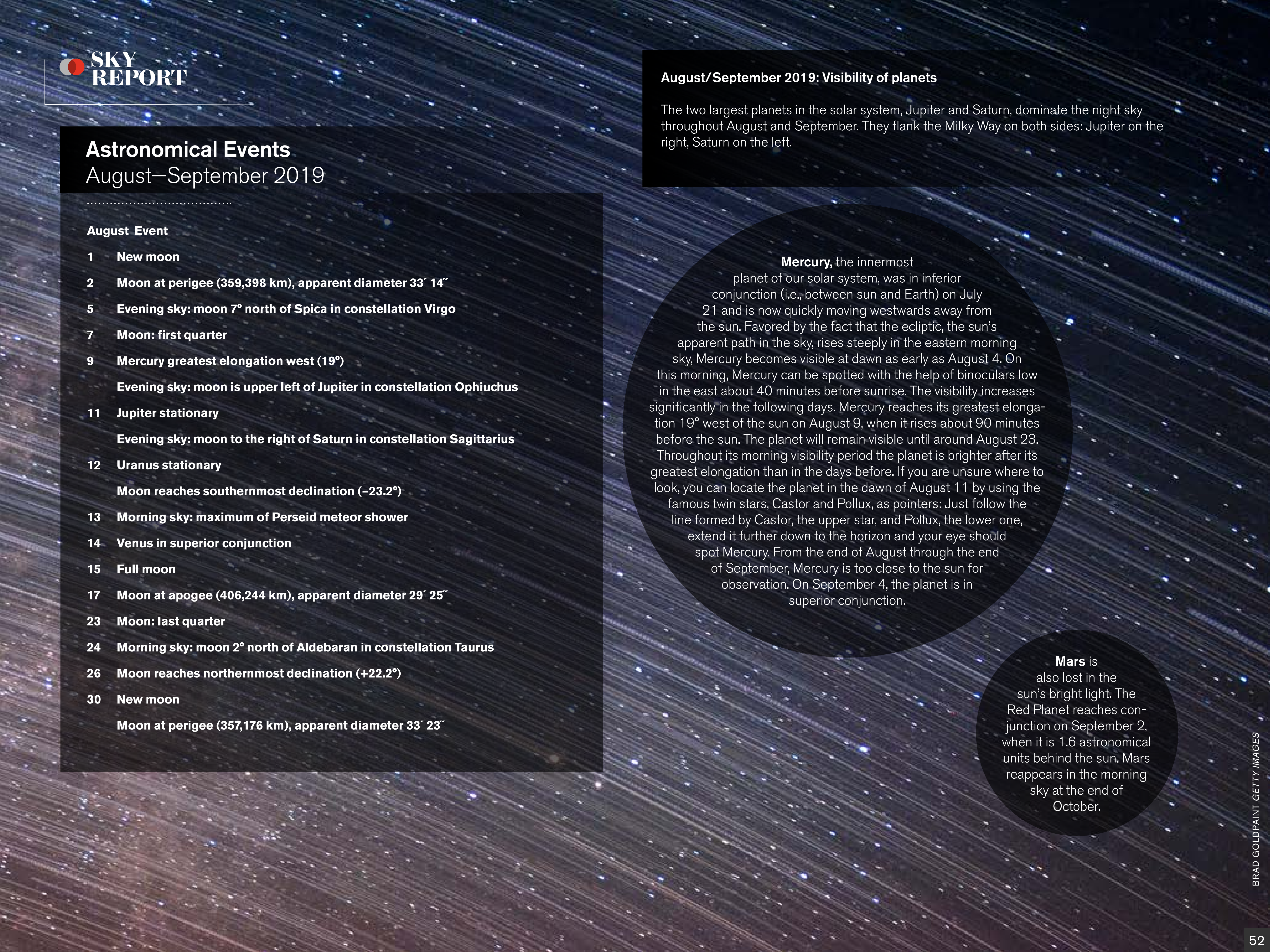

Astronomical Events
August–September 2019

August	Event
1	New moon
2	Moon at perigee (359,398 km), apparent diameter 33´ 14´´
5	Evening sky: moon 7° north of Spica in constellation Virgo
7	Moon: first quarter
9	Mercury greatest elongation west (19°)
	Evening sky: moon is upper left of Jupiter in constellation Ophiuchus
11	Jupiter stationary
	Evening sky: moon to the right of Saturn in constellation Sagittarius
12	Uranus stationary
	Moon reaches southernmost declination (–23.2°)
13	Morning sky: maximum of Perseid meteor shower
14	Venus in superior conjunction
15	Full moon
17	Moon at apogee (406,244 km), apparent diameter 29´ 25´´
23	Moon: last quarter
24	Morning sky: moon 2° north of Aldebaran in constellation Taurus
26	Moon reaches northernmost declination (+22.2°)
30	New moon
	Moon at perigee (357,176 km), apparent diameter 33´ 23´´

August/September 2019: Visibility of planets

The two largest planets in the solar system, Jupiter and Saturn, dominate the night sky throughout August and September. They flank the Milky Way on both sides: Jupiter on the right, Saturn on the left.

Mercury, the innermost planet of our solar system, was in inferior conjunction (i.e., between sun and Earth) on July 21 and is now quickly moving westwards away from the sun. Favored by the fact that the ecliptic, the sun's apparent path in the sky, rises steeply in the eastern morning sky, Mercury becomes visible at dawn as early as August 4. On this morning, Mercury can be spotted with the help of binoculars low in the east about 40 minutes before sunrise. The visibility increases significantly in the following days. Mercury reaches its greatest elongation 19° west of the sun on August 9, when it rises about 90 minutes before the sun. The planet will remain visible until around August 23. Throughout its morning visibility period the planet is brighter after its greatest elongation than in the days before. If you are unsure where to look, you can locate the planet in the dawn of August 11 by using the famous twin stars, Castor and Pollux, as pointers: Just follow the line formed by Castor, the upper star, and Pollux, the lower one, extend it further down to the horizon and your eye should spot Mercury. From the end of August through the end of September, Mercury is too close to the sun for observation. On September 4, the planet is in superior conjunction.

Mars is also lost in the sun's bright light. The Red Planet reaches conjunction on September 2, when it is 1.6 astronomical units behind the sun. Mars reappears in the morning sky at the end of October.

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Astronomical Events
August–September 2019

September	Event
2	**Mars in conjunction with sun**
4	**Mercury in superior conjunction**
5	**Evening sky: moon is upper right of Jupiter in constellation Ophiuchus**
6	**Moon: first quarter**
7	**Evening sky: moon is 6° right of Saturn in constellation Sagittarius**
8	**Evening sky: moon is 6.5° left of Saturn in constellation Sagittarius**
	Moon reaches southernmost declination (–23.3°)
10	**Neptune at opposition**
13	**Moon at apogee (406,377 km), apparent diameter 29´ 24˝**
14	**Full moon**
18	**Saturn stationary**
20	**Morning sky: moon near Aldebaran in constellation Taurus**
22	**Moon: last quarter**
23	**Equinox**
	Moon reaches northernmost declination (+22.3°)
28	**Moon at perigee (357,802 km), apparent diameter 33´ 23˝**
	New moon

August/September 2019: Visibility of planets

The two largest planets in the solar system, Jupiter and Saturn, dominate the night sky throughout August and September. They flank the Milky Way on both sides: Jupiter on the right, Saturn on the left.

Venus hides in the sun's glare during August and September. The planet passes behind the sun on August 14, when it is in superior conjunction. Until the end of September its eastward elongation increases to more than 12°. But this is not sufficient to shine brightly as an evening star, because the ecliptic is only slightly inclined to the western horizon. As a result, Venus sinks below the horizon only about 30 minutes after sunset, about the time when civil twilight ends. Venus forms a close pair in the sky with Mercury in the evenings of September 12 and 13, but this conjunction will also be hidden in the sun's glare.

Jupiter is about to cross the meridian in the south when its light becomes visible at dusk at the beginning of August. It is the brightest star-like object in the night sky and shines in the southern part of the constellation Ophiuchus (the serpent-bearer). The waxing gibbous moon is upper left of Jupiter on the evening of August 9, and to the right of Saturn two days later. One month later, on the evening of September 5, the first-quarter moon is again close to Jupiter, this time to the upper right. On other nights, when the moon's light does not interfere with observation, those who have good binoculars or a small telescope can enjoy the four Galilean moons orbiting Jupiter.

Saturn is about 30° farther to the east in the constellation Sagittarius and passes the meridian two hours later than Jupiter. Between the two planets, one can see the central part of the Milky Way, which extends vertically upwards from the horizon. Both planets seem to stand guard – one on the right, the other on the left. Indeed, both planets hardly move at all: Jupiter's retrograde motion comes to a standstill on August 11, then resuming its normal motion west to east among the stars; Saturn does likewise on September 18. The moon accompanies Saturn on the evening of August 11 and again on September 7 and 8.

SKY REPORT

August

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.

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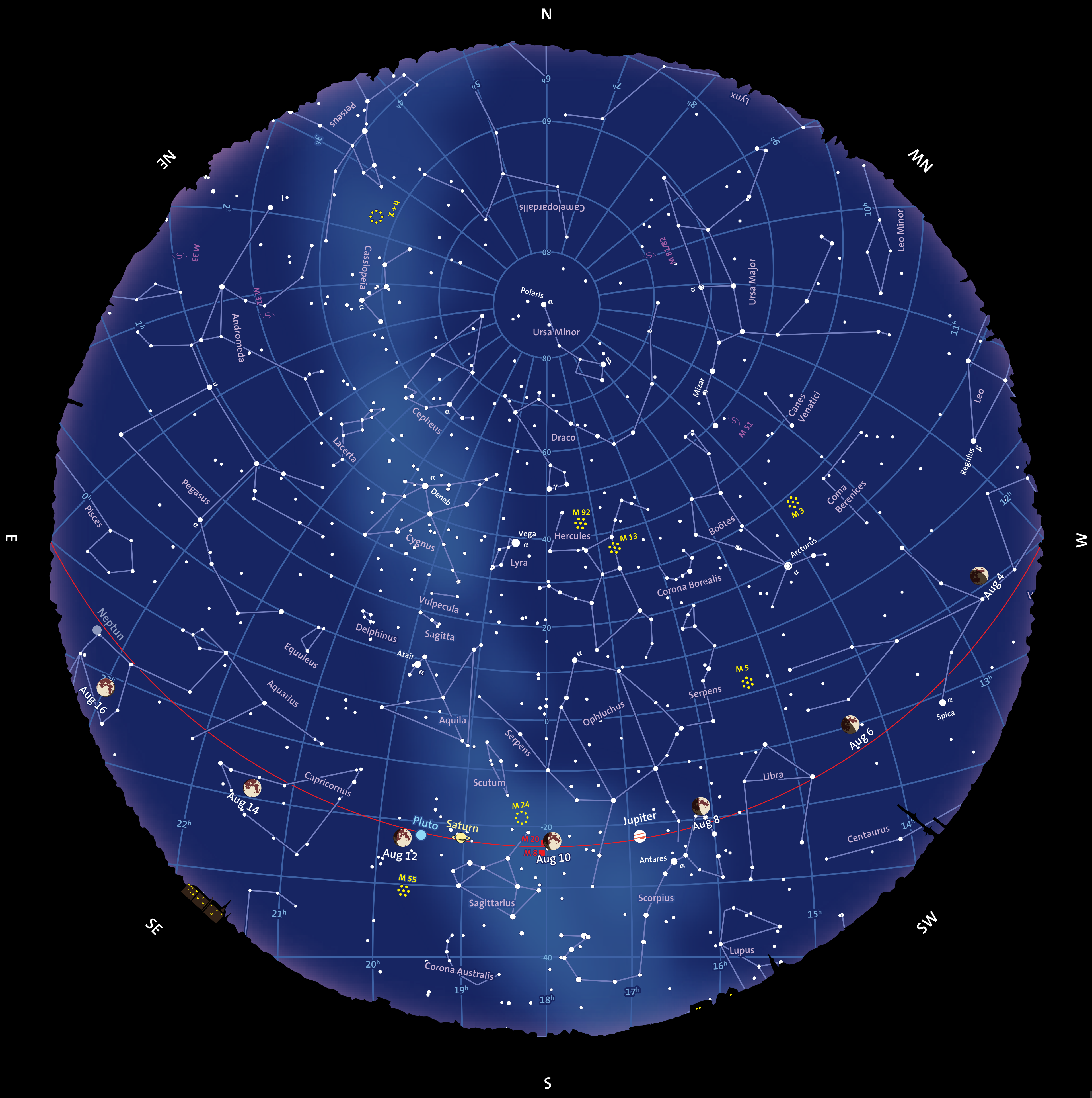
−1 0 1 2 3 4 5
Apparent magnitudes

⁘ Open cluster
⁛ Globular cluster
𝜁 Galaxy
🟥 Nebula



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SKY REPORT

September

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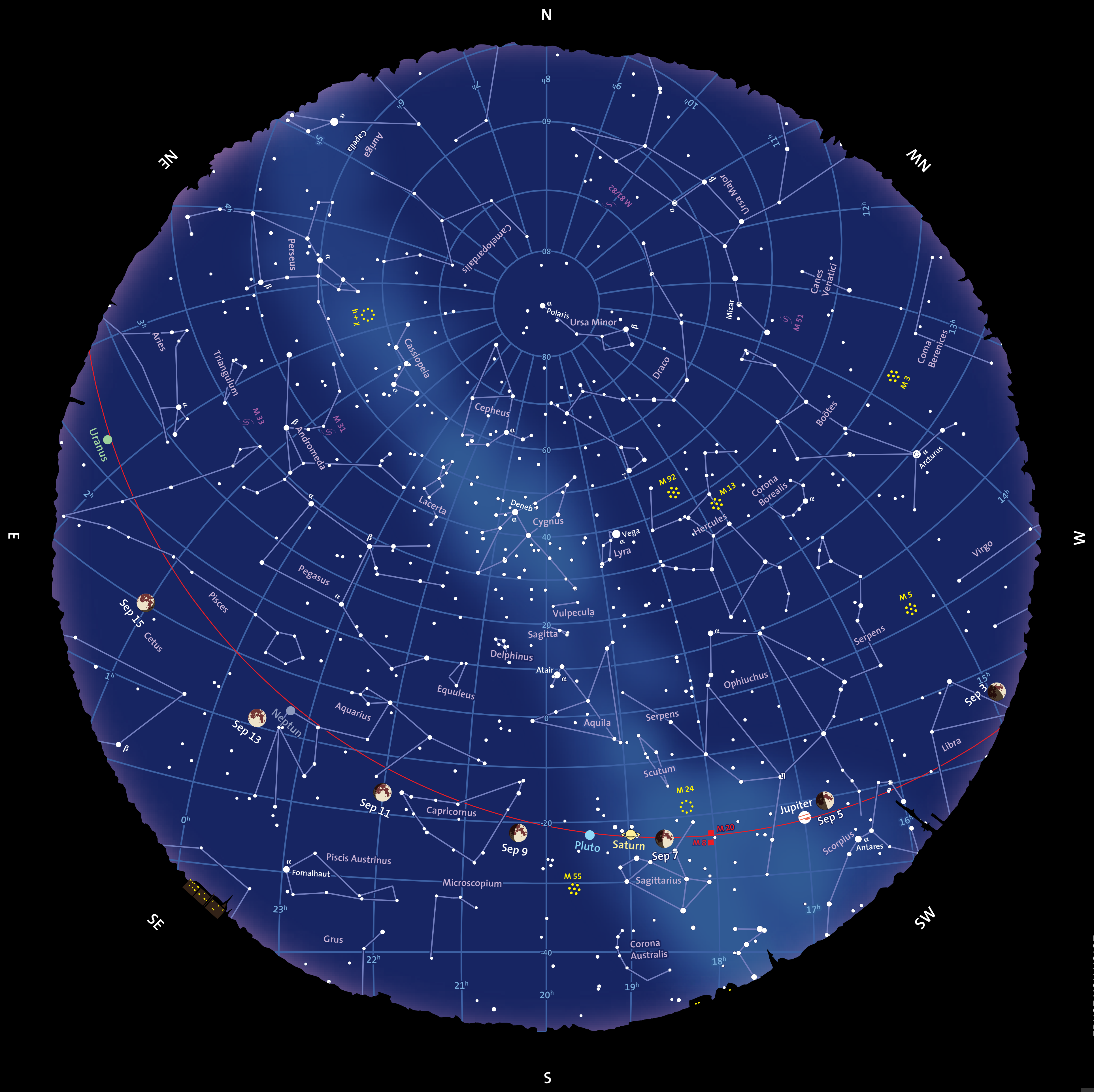
Apparent magnitudes

- ⁘ Open cluster
- ⁛ Globular cluster
- ꩜ Galaxy
- 🟥 Nebula



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SCIENTIFIC AMERICAN Space & Physics
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Plus THE SEARCH FOR PLANET NINE
A GALAXY WITHOUT DARK MATTER
SAYING GOODBYE TO STEPHEN HAWKING
nature

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