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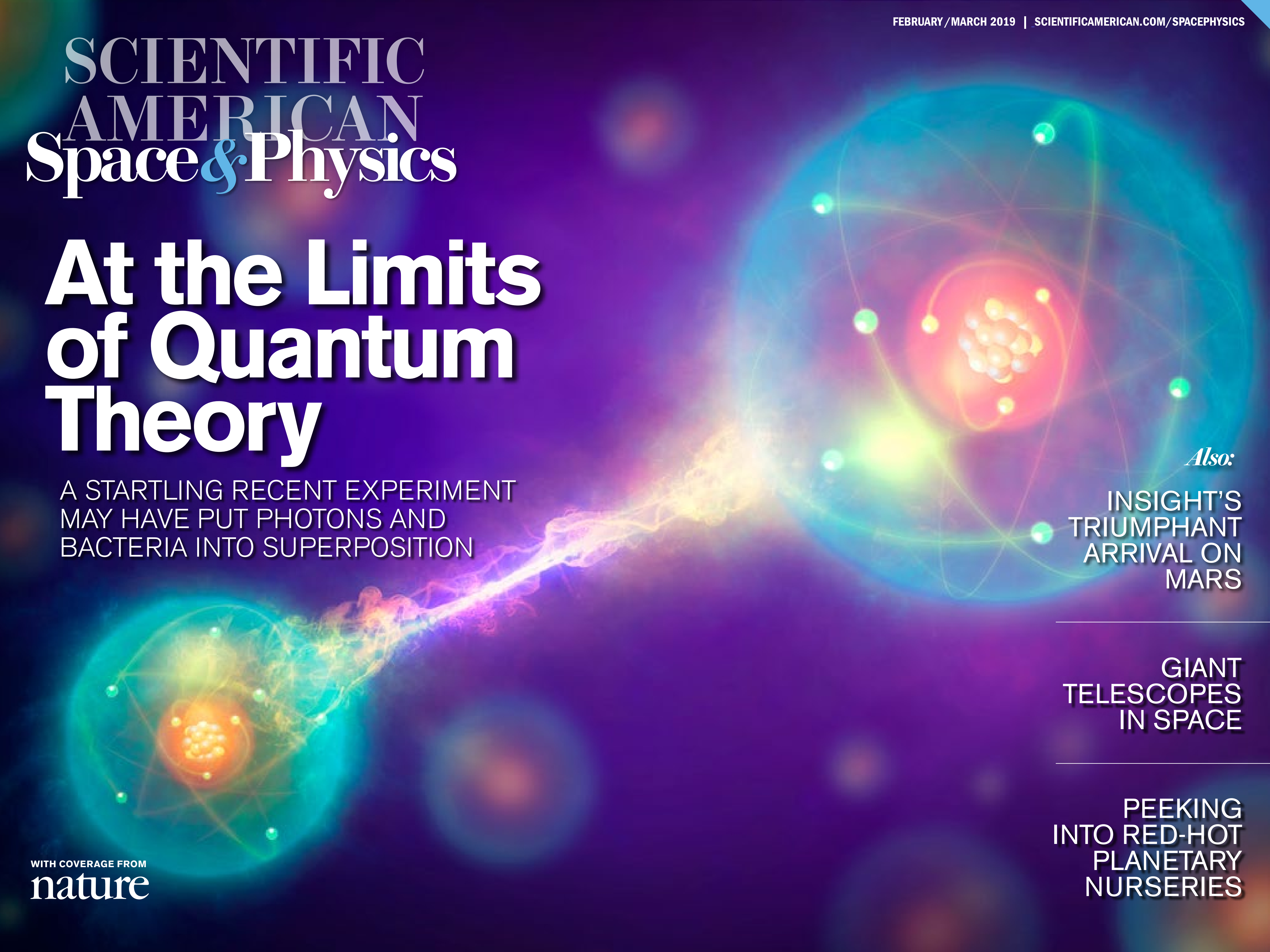

At the Limits of Quantum Theory

A STARTLING RECENT EXPERIMENT MAY HAVE PUT PHOTONS AND BACTERIA INTO SUPERPOSITION

Also:

INSIGHT'S TRIUMPHANT ARRIVAL ON MARS

GIANT TELESCOPES IN SPACE

PEEKING INTO RED-HOT PLANETARY NURSERIES

WITH COVERAGE FROM nature

LIZ TORMES

Both Here and There

For nearly a century the Schrödinger's cat thought experiment has remained that: an entirely theoretical problem in which the cat—locked in a box and exposed to a toxic substance—is simultaneously alive and dead, until the inside of the box is observed. This paradox captures the nature of quantum superposition—that an object can be in two states, or in two places, at once. Some recent research has shown some quantum effects in nature, but as JJonathan O'Callaghan writes in this issue, no one has yet managed to orchestrate superposition of an entire living organism. Using a fascinating light beam and mirror set-up, researchers at the University of Sheffield in England may have observed photosynthetic bacteria in superposition with photons (see "'Schrödinger's Bacterium' Could Be a Quantum Biology Milestone"). We may be at the cusp of an exciting phase of quantum research. At once I am both captivated and curious.

Elsewhere in this issue, Ian O'Neill reveals the promise of NASA's latest mission to Mars—the InSight Lander (see "NASA's InSight Mission"). And Lee Billings reports on the latest push by NASA and other space agencies to establish in-space assembly of mega-size telescopes (see "Finding Alien Life May Require Giant Telescopes Built in Orbit"). Enjoy!

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SPACE & PHYSICS

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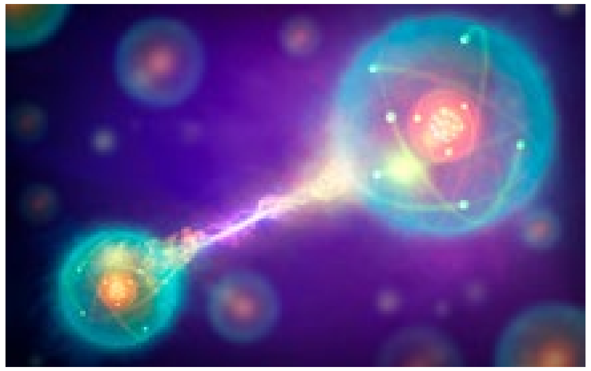

On the Cover
Exciting recent experimental results may have just pushed quantum theory into new territory

MARK GARLICK *GETTY IMAGES*

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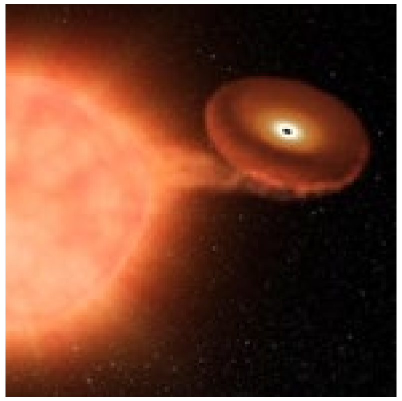

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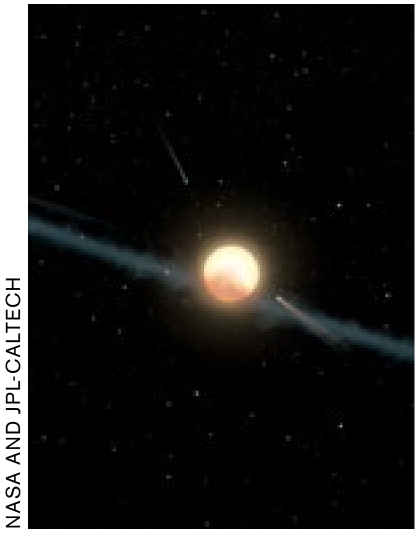

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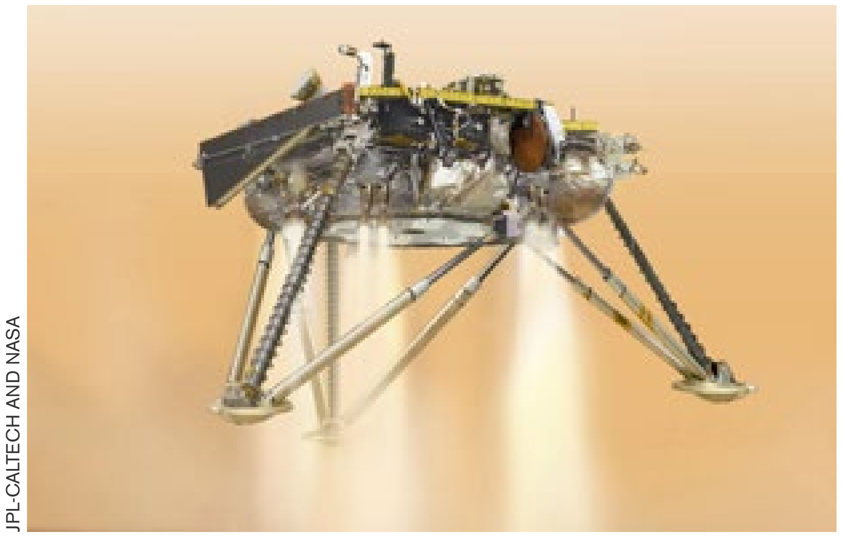

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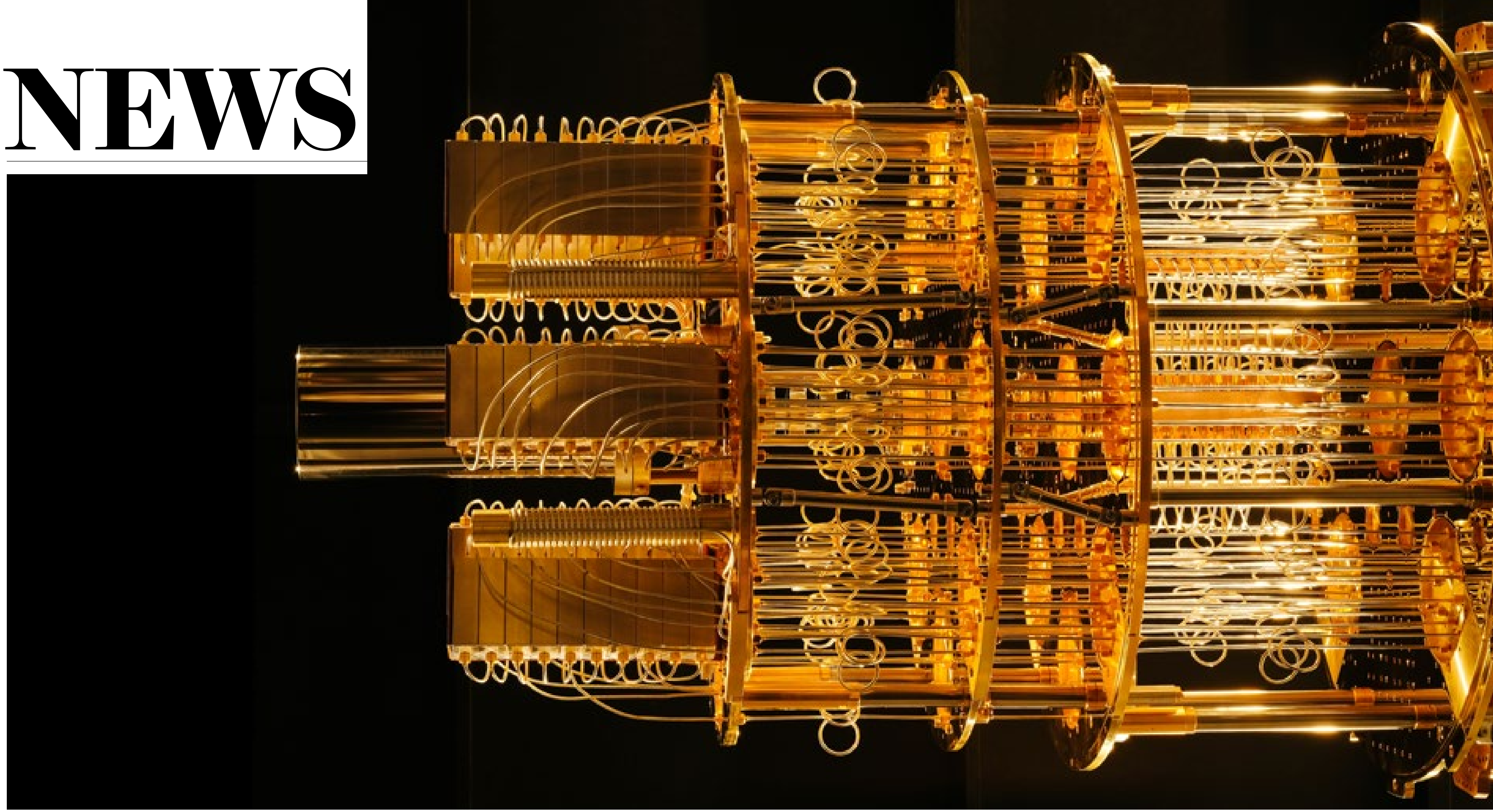


An IBM Q cryostat used to keep IBM's 50-qubit quantum computer cold in the IBM Q lab in Yorktown Heights, N.Y., on March 2, 2018.

Is the U.S. Lagging in the Quest for Quantum Computing?

U.S. government funding is needed to sustain the arduous journey toward a practical quantum computer, experts say

A QUANTUM COMPUTER capable of breaking the strongest codes protecting online communications and computer data is highly unlikely to appear within the next decade, a new report says. But leading experts still recommend the U.S. government should prepare for that eventuality as many countries race to develop practical quantum computers.

Issued by the National Academies of Sciences, Engineering and Medicine, the report prescribes a healthy dose of skepticism for the quantum-computing fever that has infected tech news headlines and press releases in recent years. Contrary to some sensational claims, quantum computers will not completely replace classical computers anytime soon, if ever. And despite a spike in commercial interest, the short-term impact on the computing industry will probably be fairly small. "I think in the next year or two we won't get to solving actual problems yet," said John Martinis, a research scientist at Google and professor of physics at the University of California, Santa Barbara, during a press conference. "But there will be better machines out there, and excitement will pick up with the understanding that we are still doing basic science."

Quantum computing's promise comes from harnessing the interactions described by quantum mechanics at the universe's smallest scales. If a bit of information is like a penny with only either "heads" or "tails" in classical computing, then a quantum bit (qubit) is somewhat like a round sphere for which one hemisphere is heads and the other is tails. By manipulating the sphere—rolling it around, for instance—one could put a qubit into a quantum state where it is 40 percent heads and 60 percent tails or 99 percent heads and 1 percent tails or evenly split 50–50. Existing quantum computers encompass a wide variety of architectures, using superchilled atoms, loops of superconducting metal and other exotic constructs as qubits.

The huge number of possible states in a single qubit could allow a quantum computer to execute much more complex computing operations than any conceivable classical computer. That raw power could be harnessed someday to perform tasks impossible for practical computers such as cracking the strongest cryptographic ciphers used by governments and companies or simulating quantum systems relevant to scientific fields such as physics, chemistry and biology. But before such feats can become a routine reality quantum computers must become much more practical and reliable.

Error, Error!

One of the greatest challenges is environmental "noise" from thermal fluctuations or physical vibrations that can disrupt the quantum states of qubits used to carry out computing operations. Those disruptions create errors that must be corrected in each affected qubit, and often emerge from the very systems engineers use to control and interact with qubits in the first place.

The end goal of the race for practical quantum computing is to create a fully error-corrected quantum computer that can handle all those noisy disruptions. Researchers are still trying to bring down error rates in quantum systems with just two-qubit operations but have not yet extended those error-correction methods to much larger arrays consisting of 50 qubits and more, which suffer from greater noise issues. "These machines are quite far away," said Mark Horowitz, a professor of electrical engineering and computer science at Stanford University and chair of the committee behind the report, during the press event. "We need to have about 100,000 times more qubits than we have today, and we need to decrease the error rates of qubits by a factor of 100."

"We need to have about 100,000 times more qubits than we have today, and we need to decrease the error rates of qubits by a factor of 100."
—Mark Horowitz

A few skeptics even suggest building a practical quantum computer is impossible. Mikhail Dyakonov, a theoretical physicist at the University of Montpellier in France, believes engineers will never be able to control all the continuous parameters that would underpin even a 1,000-qubit quantum computer. In his view, error correction faces a hopeless task of handling potential disruptions emanating from that huge number of parameters, which would exceed the estimated number of atoms in the known universe. "At this point, I say this is impossible because there are too many of them and you can't keep them all under your control," Dyakonov says.

But it is possible to reduce the number of errors to a manageable amount, says Daniel Lidar, director of the Center for Quantum Information Science and Technology at the University of Southern California and an independent reviewer for the report. This involves encoding a stable logical qubit based on many noisy physical qubits working together to detect and correct errors—a bit like having underperforming students working together to triple-check one another's work and create a more reliable team. "[B]y using more physical qubits per logical qubit, it becomes possible to correct more errors—and a threshold 'noise level' can be reached, below which a quantum computer that computes using its logical qubits is effectively noiseless," he says. "The key to this is the digitization of continuous errors due to the use of quantum error correction."

For now even noisy quantum computing devices without error correction could offer a useful "stepping stone" by demonstrating "quantum supremacy," and completing any task that would stymie even the most powerful classical computers, Lidar says. But achieving quantum supremacy would still be easier than the next major milestone: commercially viable quantum computers that can perform practical tasks more efficiently than classical computers. That crucial step, he says, may require a combination of error-correction and error-suppression methods reducing the baseline number of qubit errors to make practical quantum computing more scalable.

Prepping for a Quantum Future

The U.S. could still benefit from a better-safe-than-sorry approach even if quantum computing progress proves slow, said Bob Blakley, global director of Information Security Innovation at CitiGroup and co-author of the report. He said it would not hurt to develop and implement new "quantum-safe" cryptographic algorithms, especially because existing ciphers require regular refreshment anyway to minimize the chance of being cracked. "Even if we didn't think quantum computing was likely to exist in 50 years or 100 years, we would still be engaged in an effort to replace the current generation of cryptographic algorithms on about the schedule we're replacing them with quantum-safe algorithms," he said.

The U.S. intelligence community may already be thinking along those lines, given the new report was written in response to a request from the Office of the Director of National Intelligence. But private investment in quantum computing has also been on an upswing. Leading tech companies such as Google, IBM and Intel have been developing their own test versions of quantum-computing architecture, along with start-ups such as D-Wave Systems in Canada and the U.S.-based Rigetti Computing.

If quantum computers fail to prove commercially viable in the short term, quantum-computing research may need additional backing by the government. Until now federal funding for quantum computing research has been sporadic and spread out in uncoordinated fashion among various agencies. That should change with the National Quantum Initiative Act, which was introduced as legislation in July 2018 and aims to provide $1.275 billion in funding for a 10-year research effort. The bill cleared both chambers of Congress and was signed into law by President Trump in December.

The initiative likely received a boost from both the report's findings and from growing fear of the U.S. falling behind as other countries step up. China has announced an $11.4-billion national quantum-computing effort. Similarly, the European Union has committed $1.1 billion over 10 years. The U.K. is investing $358 million over five years. Even Australia and Canada have launched their own initiatives.

"It's going to be easy to cede the lead here to other countries that are taking a proactive and aggressive approach," Lidar says. "We absolutely must have a national direction that is well funded and enjoys bipartisan support."

—Jeremy Hsu

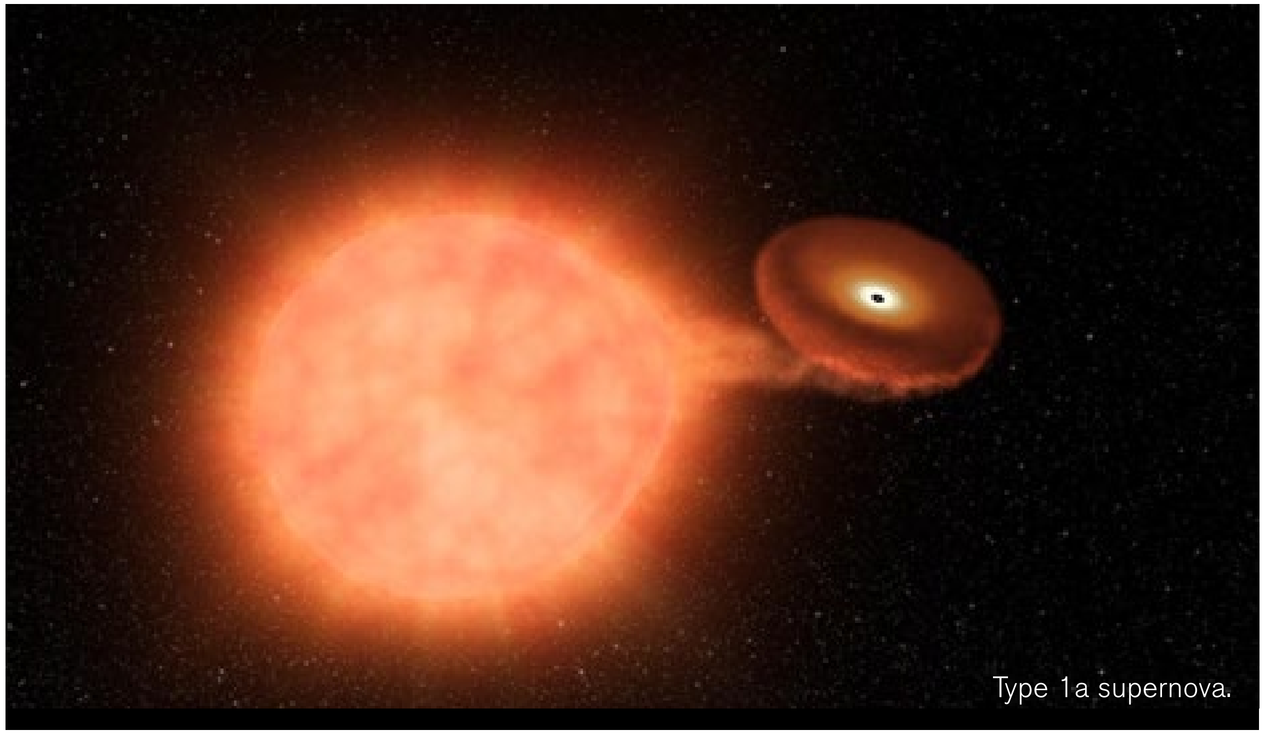
Caught in the Act—Astronomers Get Their Best Look Yet at a Supernova Blowing Up

New observations of a stellar explosion have revealed a surprise that could point to the trigger behind these violent, yet mysterious, eruptions

GEORGIOS DIMITRIADIS thought he had botched the data. It was late on a Friday night and the University of California, Santa Cruz, astronomer was the last one in the office. He had been waiting anxiously for NASA's planet-hunting Kepler space telescope to stream a batch of data toward Earth—not because he wanted to scour the observations for signs of exoplanets but because he was looking for a supernova.

See, Kepler was designed to do one thing remarkably well: Monitor stars so closely that it could catch tiny flickers in brightness. That made it ideal for finding exoplanets (that obscure their host stars' light)—as well as making an array of other observations such as recording the rise and fall of light emitted during a star's death throes. So when Kepler's mission was extended, astronomers decided the telescope should scour more than 20,000 galaxies in order to catch as many supernovae as possible. And when one erupted in a spiral galaxy only 170 million light-years away last January, Dimitriadis knew it would be the best look yet at the first moments behind the cosmic detonation.

But the data provided a better record than he had even hoped for. "I thought I had done something wrong—not because there is noise, but because it was so good," Dimitriadis says, explaining astronomers typically miss the first few days or even weeks after a supernova explodes and then monitor it once every night. That gives them relatively few data points. But here astronomers had images before the explosion and every 30 minutes thereafter. "I had never seen something like this before," he says. What is more: The supernova's brightness rose sharply during those early moments, creating an unexpected "bump" in the graph of its changing light over time, called a light curve. Dimitriadis circled that


Type 1a supernova.

bump in red and drew an arrow toward it with three question marks before sending the light curve off to his collaborators. They have since analyzed that bump—in an attempt to determine the eruption's hidden trigger—in a new paper accepted for publication in *The Astrophysical Journal Letters* and available online.

The object, designated SN 2018oh, belongs to a class called "type Ia" supernovae. These eruptions each detonate at roughly the same luminosity and can therefore be used as cosmic beacons to measure the vastness of the cosmos. (Because astronomers know how bright these objects are in reality and how bright they appear on Earth, they can calculate the distance to the far-off explosion.) For this reason they are commonly referred to as standard candles. And because they are so standard, astronomers have long assumed they are like fireworks built in a cosmic assembly line—each one constructed the same way as the next. But there is one major hiccup: Although each is set off by the death of a white dwarf—a burnt-out, roughly Earth-size remnant of a sunlike star—these objects are too stable to explode on their own. Instead, there must be a hidden assassin. And astronomers have long-argued over whether that assassin is a second white dwarf or a giant star. If it is a white dwarf, then the two stars will spiral toward each other and collide in a violent explosion. If it is a larger star, then the white dwarf will steal material from this companion until it can no longer support its extra weight, and ultimately blows itself to smithereens.

Which assassin is the true culprit? That has been a mystery for 50 years, but SN 2018oh just might reveal an important clue from the cosmic crime scene. In the second scenario the companion star does not spiral inward, but rather survives—leaving a trail of evidence behind. In 2010 Daniel Kasen, an astronomer at the University of California, Berkeley, and a co-author on the paper, predicted that in this scenario the ballooning cloud of debris from the supernova will run into the surviving companion star—a process that heats the wreckage and causes the debris to brighten—thus creating a bump in the early light curve. And just like the hottest part of a flame is blue, that bump should similarly be blue.

NASA AND JPL-CALTECH

Astronomers have long searched for this signature and have even spotted a handful of supernovae where abnormal data points could point toward this elusive blue bump—but none were as obvious as this. Dimitriadis and his colleagues argue this is the best evidence yet for a massive companion star.

But others, like Benjamin Shappee, an astronomer at the University of Hawaii at Mānoa, disagree. In a second paper also submitted to *ApJ Letters* and available online Shappee and his colleagues argue for the first scenario instead—the one where two white dwarfs spiral in toward each other to set the supernova in motion. Here, there is no surviving companion star. So how does Shappee explain the early bump? His team argues it is caused by a blob of radioactive material at the surface of one of the white dwarfs that glows prior to the supernova's peak brightness—thus explaining the early light bump. And it is not such a wild idea: Although there are many different models that describe the dangerous tango between white dwarfs, one popular model predicts such a dollop of radioactive stuff on the star's crust.

Both teams agree there are strikes for and against each scenario—admitting better theoretical models and future observations are needed to push these hypotheses forward. Indeed, Craig Wheeler, an astronomer at the University of Texas at Austin who was not involved in either study, is not convinced of either scenario. "That kind of data at those very early times, within the first minutes or hour after the explosion, are exceedingly rare," he says. "Whether they have given us the commanding piece of information that resolves all our issues—I think probably not."

Regardless of which scenario wins, it looks like these objects can form via two different stellar assembly lines, argues Ryan Foley, an astronomer at U.C. Santa Cruz and a co-author on Dimitriadis' study. "Even if you don't want to say that this is a collision with a companion star, it's still a problem because we know that not all type Ia supernovae have this sort of bump," he says. "So, at the very least, there's something going on with the explosion that creates this diversity in the first few days after an explosion." How do these supernovae maintain such "standard candle" luminosities when they actually follow different paths? In fact, their brightness can vary a bit, but in a very predictable way that astronomers can correct for because the brightest supernovae fade more slowly than their dimmer kin do.

Luckily, the explosions' role as cosmic milestones is on solid ground, but a better understanding of their diverse causes will only improve the precision of the measurements based on them. Or, as Foley says, "the broad strokes won't change, but it can matter in the details." And those details are crucial if astronomers want to unravel the great cosmic mysteries of our time, like dark energy—the poorly understood phenomenon that propels the expansion of the universe—for example. Only a precise measurement of the expansion rate throughout cosmic history (garnered by distances measured with the help of type Ia supernovae) will allow astronomers to discover whether dark energy has changed over time and therefore pin down what it actually is.

But it all depends on that deadly tango and whether these stars dance with a variety of companions—from the massive stars that lend them more gas than they can handle to their twins that may crash into them.

—Shannon Hall

Voyager 2 Spacecraft Enters Interstellar Space

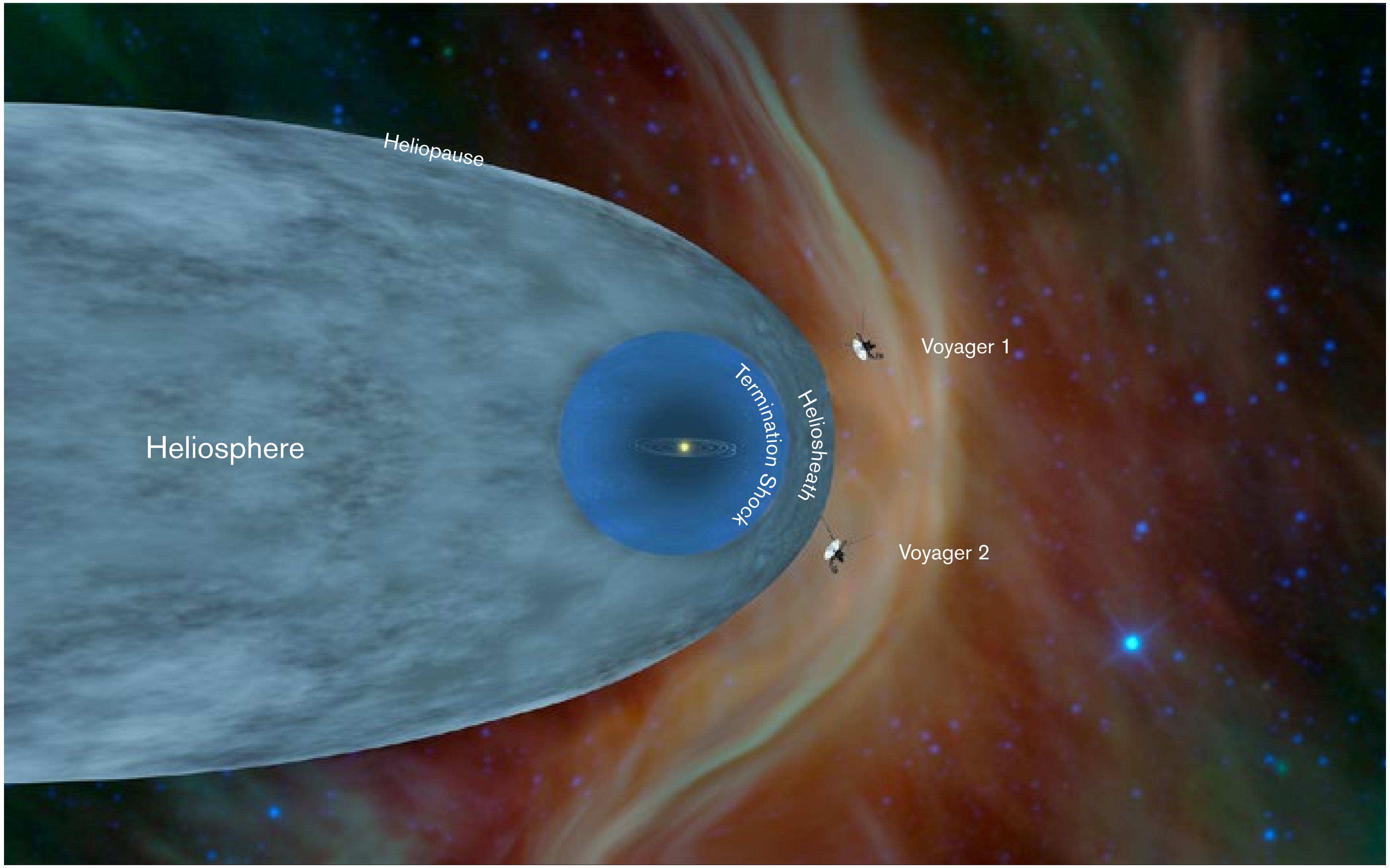
After a journey of more than four decades, Voyager 2 has passed beyond the sun's influence

NASA'S VOYAGER 2 spacecraft has crossed into interstellar space, agency officials announced in December.

The milestone makes Voyager 2 humanity's second operating spacecraft in history to go interstellar after the Voyager 1 spacecraft did in August 2012. "One kind of feels like a lucky fluke," says Justin Kasper, a scientist involved in the Voyager missions from the University of Michigan in Ann Arbor. "Two feels like we're becoming a society that's capable of exploring interstellar space."

Voyager 2's new interstellar status is based on data from its Plasma Science Experiment (PLS), which logged a decrease in particles around the spacecraft that had been ejected from our sun. The PLS measurements of this "solar wind" plummeted to zero on November 5—the official date of Voyager 2's departure. Now the mission team is confident the spacecraft has joined its predecessor in passing beyond a key boundary called the heliopause and into interstellar space. "November 5 was the day that the galactic cosmic-ray intensity abruptly increased, and that same date was when the heliospheric particle intensity dropped significantly," says Voyager project scientist Ed Stone. "That same day the magnetic field increased, and that's also the point at which the plasma [instrument] quit measuring the solar wind. So that's the correlation we were looking at [to confirm interstellar space]."

The heliopause is the region at which the solar wind's outward expansion is countered by the influence of incoming interstellar particles. It is considered to be one of the limits of the sun's influence on surrounding space—although the two spacecraft are still said to be inside the solar system, they are now in a region of space dominated more by the Milky Way Galaxy than our sun. Prior to this, Voyager 2 crossed a region known as the termination shock back in 2007, where the speed of the solar wind dropped dramatically as it began to encounter interstellar particles and radiation. The entire region of the sun's bubble of influence in the galaxy is known as the heliosphere, whereas the region Voyager 2 has just traversed is called the heliosheath, which lies between the termination shock and the heliopause.



This illustration shows the position of NASA's Voyager 1 and Voyager 2 probes beyond the heliosphere, a region of space dominated by our sun that extends well past the orbit of Pluto.

JPL-CALTECH AND NASA

NASA launched the twin Voyager spacecraft in 1977 on a mission to explore the outer planets. After both studying Jupiter and Saturn—with Voyager 2 taking a detour to also visit Uranus and Neptune—the two probes continued their journeys toward the edge of the solar system. In August 2012 Voyager 1 became the first human-made vehicle in history to reach the heliopause and enter interstellar space. But both missions have raised questions about our solar system's true boundary. Originally some scientists speculated our star's winds would peter out in the vicinity of Mars, but the Voyager spacecraft have gradually pushed this boundary far beyond. The solar system's actual limit remains contentious, however, with some researchers defining it not by solar winds but rather by the most distant objects thought to be held in thrall by our sun's gravity—comets in the Oort Cloud up to about two light-years away. Regardless of where one believes the sun's sphere of influence ends, both Voyagers are poised to greatly extend it—each has a famous Golden Record onboard in the event any other spacefaring species happens across them on their lonely, eons-long sojourns between the stars.

Voyager 2 has traveled about 120 astronomical units—one AU is the Earth–sun distance—which equates to just over 18 billion kilometers, a distance light itself takes more than 16 hours to traverse. Although far out, this is about one AU closer in than Voyager 1's earlier exit from the solar system. The most obvious explanation for this disparity is that our solar system's heliosphere is not perfectly spherical—instead it is oddly shaped and asymmetric, perhaps due to the influence of the Milky Way's magnetic field. "You can think of the galactic magnetic field as an array of bungee cords," says Eric Christian from NASA's Goddard Space Flight Center, a scientist on the Voyager team. "The solar system is this soccer ball you're pushing through these bungee cords," flexing and distorting its shape as it moves.

Another possible explanation is the sun's fluctuating activity, measured via outbursts such as solar flares and powerful explosions called coronal mass ejections. These events can affect the heliosphere much like gas pumped into a balloon, causing it to grow—conversely, when their numbers decrease the heliosphere can shrink, changing the location of the heliopause. It is possible that in coming years, as the sun reaches the peak of its roughly 11-year activity cycle, its outbursts could push the heliopause farther out again, perhaps even beyond Voyager 2. "There's a chance [the probe could enter interstellar space twice]," Kasper says. "It's all going to depend on how long the solar minimum lasts." In fact, something like this happened when Voyager 2 crossed the termination shock in 2007. Fluctuating solar activity made the boundary oscillate, so the spacecraft ended up crossing the termination shock several times.

Voyager 2 is also entering interstellar space in a completely different region from its sister ship. Whereas the latter traveled out of the heliosphere's northern hemisphere (the planet-filled ecliptic plane is the equator), Voyager 2 is heading out of the southern hemisphere. Here, the galactic magnetic field is thought to be weaker, which may also affect the shape of the heliosheath. Having outbound spacecraft from both heliospheric hemispheres opens up fascinating opportunities for science. Both spacecraft have a working magnetometer, to measure the local magnetic field, and two particle detectors—one for solar particles and another for incoming cosmic rays. Only Voyager 2, however, continues to have a functioning plasma instrument, which could tell us much more about this unexplored region, including the temperature, density and velocity of any electrically charged material flowing around the spacecraft.

The Voyager team will continue to take measurements as both spacecraft travel away from the sun into a region called the outer heliosheath, although neither probe has much time remaining to make observations. "We're probably only going to have four to five years left of data," Christian says. But they may later be joined in this region by other spacecraft in the coming years. Although NASA's Pioneer 10 and 11 spacecraft launched before the Voyagers paved the way on similar journeys beyond the asteroid belt to the outer solar system, eventually leading into interstellar space, they are no longer communicating with Earth. But NASA's New Horizons spacecraft, which flew by Pluto and has conducted the most distant-ever rendezvous in the solar system, could continue operating into interstellar space, giving us a third functioning interstellar probe in coming decades.

–Jonathan O'Callaghan

First Hint of Near-Room-Temperature Superconductor Tantalizes Physicists

High-pressure hydrogen materials could be a step toward a new era of superconductivity

A lanthanum-based compound seems to act as a superconductor at near-room temperature.

SUSAN E. DEGGINGER *ALAMY*

PHYSICISTS THINK THEY have achieved one of the most coveted goals of their discipline: creating a superconducting material that works at near-room temperature.

The evidence is still preliminary and comes with a major caveat. So far, the material has been made only under pressures of about 200 gigapascals: or two million atmospheres.

But if confirmed, the feat would be the first example of superconductivity above 0 degrees Celsius, and some physicists say that the work could be a milestone in the study of superconductivity, which researchers hope will one day make the generation, transmission and use of electricity vastly more efficient.

"Long-Held Dream"

"The observation is amazing," says Yanming Ma, a physicist at Jilin University in Changchun, China, although he cautions that the work is in its early stages. Getting to room temperature has been "a long-held dream," Ma says, ever since superconductivity was discovered more than a century ago.

Russell Hemley, a geophysicist at George Washington University in Washington, D.C., first announced evidence of this feat at a conference in August. His team is now publishing the results in *Physical Review Letters.*

The authors report seeing a sudden drop in electrical resistance at 7 degrees C in a material they synthesized: a "superhydride"—a compound that contains a large amount of hydrogen—of lanthanum, LaH_{10}. Such a drop is the hallmark of a phase transition to superconductivity that occurs when the material is cooled below a threshold temperature. "We're very confident that we see a transition," says Hemley.

The achievement of superconductivity above 0 degrees C has no particular physical meaning, but it is "enormously important psychologically," says Mikhail Eremets, a physicist at the Max Planck Institute for Chemistry in Mainz, Germany. In 2014, Eremets' team showed that another hydrogen compound—hydrogen sulfide—becomes a superconductor at what was, at the time, the record high temperature of -83 degrees C for superconductivity.

Record Highs

In their experiment, Hemley and his collaborators placed a diamond anvil in a synchrotron beamline at the Argonne National Laboratory, outside Chicago in Illinois. They used the anvil's diamond tips to squeeze a minuscule sample of lanthanum and hydrogen to pressures of up to 200 gigapascals. Next, they temporarily heated the compound and watched its structure change along with its conductive properties, monitoring the process with x-ray diffraction.

The researchers produced a new structure—the LaH_{10}—which previous simulations by their team and others, including Ma's, suggested would be superconducting at very high temperatures.

They allowed it to cool—while keeping it at high pressure—and measured its electronic properties. In certain conditions, they saw the electrical resistance drop at a temperature of 280 kelvin, or about 7 degrees C.

The evidence presented in Hemley's paper has yet to convince Eremets. Follow-up experiments in his own lab suggest that the material's transition temperature is not quite as high as 7 degrees C, although it still comes in at an impressive -23 degrees C.

Hemley says that in as-yet unpublished follow-up work, his team detected another important sign of superconductivity: the material expelled existing magnetic fields from itself. The phenomenon is considered to be gold-standard evidence of superconductivity and, if confirmed, could clinch the team's claim.

Just the Beginning

Compounds such as the lanthanum superhydride made by Hemley's team, and the hydrogen sulfide studied by Eremets in 2015, are conventional superconductors, meaning that their physical properties have been well understood since the 1950s. Conventional superconductors with room-temperature transitions have been predicted for several decades, but only recently have these predictions begun to be tested in the lab.

More-exotic superconductors discovered since the 1980s have, until recently, boasted record-high transition temperatures, but are yet to achieve room-temperature superconductivity and their theoretical underpinnings are unexplained.

Hemley says he is confident that other materials exist—beyond even those explored in simulations—with even higher transition temperatures.

And he adds that his team's experiments could offer hints on how to develop materials that might have similar electronic properties at less extreme pressures. "This is just the beginning of a new era of superconductivity," says Hemley.

—Davide Castelvecchi

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Have Astronomers Found Another "Alien Megastructure" Star?

Scientists now have a second example of a strange stellar phenomenon speculatively linked to extraterrestrial intelligence in 2015

A FARAWAY STAR IN the southern sky is flickering in an odd manner that suggests a bizarre cloud of material—or something even stranger—is in orbit around it. Discovered by astronomers using a telescope in Chile, the star is reminiscent of two other enigmatic astrophysical objects, one thought to harbor a planet with rings 200 times larger than those of Saturn, the other most famous for the remote possibility it is encircled by "alien megastructures." The newfound star may help shed some light on one or both of these puzzling objects.

In 2010, the Vista Variables in the Via Lactea (VVV) survey began its project of creating a three-dimensional map of variable stars in the vicinity of the Milky Way's center. As part of the project, astronomer Roberto Saito of the Federal University of Santa Catarina scoured the telescope's data for eruptive outbursts from the hundreds of millions of monitored stars. But the most notable thing he found was not an outburst at all—it was a star that grew mysteriously dim over several days in 2012. He and his colleagues reported their findings in a recently published paper in the *Monthly Notices of the Royal Astronomical Society*.

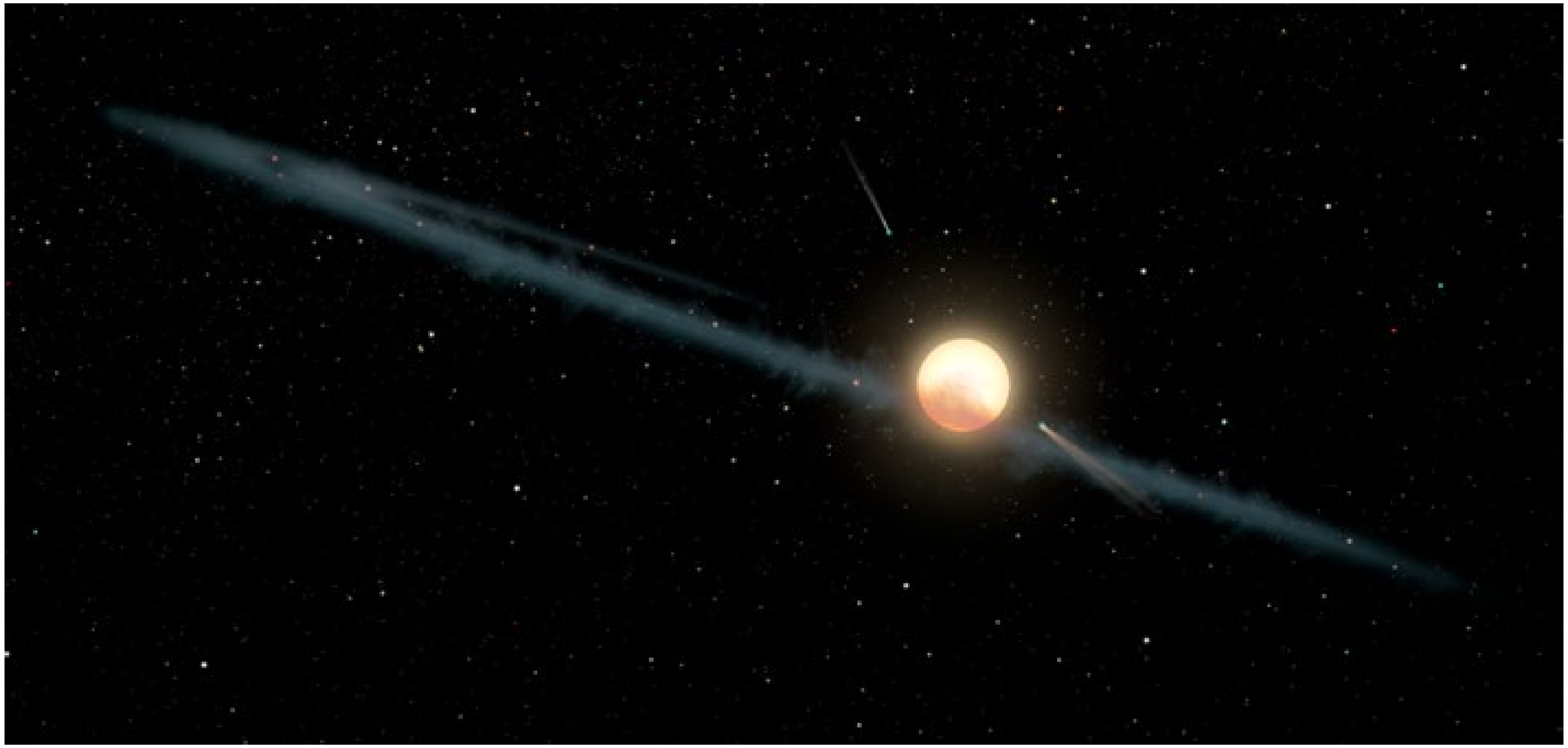
Known as VVV-WIT-07, the star appears to be much older and redder than our sun, although the amount of interstellar dust between our solar system and the star's home closer to the galactic center makes exact classification and distance measurements very difficult. What is certain is that in the summer of 2012, the object's brightness faded slightly for 11 days, then plummeted over the following 48 days, suggesting that something blocked more than three quarters of the star's light streaming toward Earth. But what could that "something" be?

According to Eric Mamajek, an astrophysicist at NASA's Jet Propulsion Laboratory unaffiliated with the VVV survey, such a profound degree of dimming suggests that a staggeringly large object or group of objects is blocking the light. "It's got to be over a million kilometers wide, and very dense to be able to block that much starlight," he says. Mamajek should know: He led the team that discovered J1407, another strange star periodically eclipsed by a planet-sized object thought to boast a massive ring system some 200 times broader than that of Saturn. In this latest case, he says, the strange signals from VVV-WIT-07 could arise from clumps or clouds of material passing between Earth and the star, though he cautioned that the data were preliminary and more observations are required.

Tabetha Boyajian agrees. Boyajian, an astronomer at Louisiana State University, was the lead author for the 2015 paper announcing the strange dimming of KIC 8462852, also known as Tabby's Star, an unusual object first spotted by NASA's Kepler Space Telescope. VVV-WIT-07 would have to harbor "a very peculiar kind of dust cloud to make these kinds of dips," Boyajian says. Boyajian's study helped spark a surge of public interest in Tabby's Star because the star's unusual dimming could be seen as evidence of an alien civilization building an artificial structure that soaked up the star's light. More conventional explanations include a swarm of comets or fragments from a shattered planet, both of which would create significant clouds of dust and debris that could also occlude the star's light. But, so far, no simple single explanation fits the complexities of the dimming seen around the star; researchers remain stymied in their attempts to understand the true nature of the strange dimming of Tabby's Star.

Astronomers track such dips by plotting the intensity of a star's light over time, a figure known as a "light curve." The light curve of J1407 shows its massive rings can occasionally block as much as about 95 percent of the star's light, while the light curve of Tabby's Star suggests that whatever orbits there only occludes about 20 percent of that star's luminous emission. That makes VVV-WIT-07 an intermediate case, Saito says. "Our object is similar in the sense that we are also trying to explain the behavior in the light curve based on material surrounding the star," he says.

Based on their data, including follow-up observations made in 2016, Saito and his colleagues speculate



An artist's rendition of a hypothetical warped band of dust around KIC 8462852, also known as Tabby's Star. This is but one of several potential explanations for the star's strange flickering, and could be a factor in a second newfound star also exhibiting similar behavior.

NASA AND JPL-CALTECH

that the star may continue to flicker into 2019, potentially displaying four additional dimming events throughout the year as the mysterious light-blocking material continues its orbit around the star. If those predictions are borne out, they could prove key to unlocking not only the mysteries behind VVV-WIT-07 but also those surrounding Tabby's Star.

"Having a sample of two, we can have two stars to study instead of one to try to unify a theory of whatever is going on," Boyajian says. If both stellar dimmings are caused by the same natural process, it makes it less likely that something unusual is happening—like super-sized cosmic construction projects.

There is hope that more of these peculiar flickering stars may show up in the near future. Saito says that it is possible the VVV survey could discover more, even though it is not optimized for identifying such systems. The Large Synoptic Survey Telescope (LSST), an 8.4-meter instrument under construction in Chile, could up turn up more members of the odd collection when it begins operations in the 2020s.

"I think we're going to start finding more objects like this in the LSST era," Mamajek says. "We're probably going to start discovering weird variable [stars] that have not been seen before."

For now, Saito and his colleagues plan to continue observing VVV-WIT-07 with infrared instruments on the ESO's New Technology Telescope and the National Optical Astronomy Observatory's Southern Astrophysical Research Telescope, both of which contributed to the team's 2016 observations. The star's intrinsic faintness—as well as the attenuation of its light across vast galactic distances—means that it is best observed at near-infrared wavelengths where interference from interstellar dust is minimal. Although the VVV Survey concluded last year, an extended survey is still observing the galactic center and may turn up other eclipses missed in the initial observations.

Hopefully these observations will shed some light on what is causing the bizarre dimming of VVV-WIT-07. "This is certainly not a common phenomenon," Mamajek says. "I can't wait to see the future results."

—Nola Taylor Redd

Gravitational-Wave Astronomers Detect Hints of Largest Black Hole Merger Yet

Physicists at the LIGO experiment have now detected 11 cosmic events that produce ripples in the fabric of spacetime

ASTRONOMERS HAVE announced a new batch of discoveries of gravitational waves—ripples in spacetime caused by cataclysmic cosmic events.

The haul consists of four mergers of black holes that were detected—but not disclosed—in 2017, including a hint of the largest such merger yet, which produced a black hole more than 80 times as massive as the sun.

The studies were posted on the website of the Laser Interferometer Gravitational-wave Observatory (LIGO) collaboration and appeared on the arXiv repository on December 3.

LIGO made the first historic detection of gravitational waves, from a black hole merger, in 2015, and has reported a smattering of other wave-producing events since. The latest data release brings the total cache to 10 black hole mergers, and the collision of two neutron stars. That event was also observed by a coterie of other instruments—from radio telescopes to space-based gamma-ray observatories—and helped to solve a slew of cosmic mysteries.

All 11 events were seen by LIGO's two interferometers, in Louisiana and Washington State, and two of them were also seen by Virgo, the slightly less sensitive observatory in Italy.

The observatories had particularly striking series of successes in August 2017: in addition to the neutron stars, they saw four black hole mergers that month. Virgo scored its first-ever detection on August 14, contributed data to the August 17 neutron-star search and then saw another merger on August 18. "And then I was out of cigars," says Jo van den Brand, a physicist at the National Institute for Nuclear and High-Energy Physics (Nikhef) in Amsterdam and the spokesperson for the Virgo Collaboration.

To put together the catalogue, the international LIGO-Virgo collaboration reanalyzed data from the events that it detected in real time in its first run, in 2015 and early 2016, and in the second one, which started in late 2016 and finished in 2017.

In particular, improved data-analysis techniques have enabled the team to reclassify an event from October 2015—less than one month after LIGO's first detection on September 14—as a bona fide black hole merger. Previously, they had only described it as a "candidate" event.

The group also performed an "off-line" analysis and found events that had not been spotted before. "We decided to wait until the off-line analysis is finished, and to publish all the black holes in one go," says Karsten Danzmann, a physicist at the Max Planck Institute for Gravitational Physics in Hanover, Germany.

The off-line findings included the 80-solar-mass monster, dubbed GW170729 according to its date. It was detected with a lower level of confidence than the others, but the team still decided to include it in the catalogue. "GW170729 still is most likely a real event," says Cole Miler, an astrophysicist of the University of Maryland in College Park who is not part of the collaboration.

In addition to the 11 events, the catalogue discloses for the first time more than a dozen "marginal" triggers. These are events recorded by at least two interferometers that recorded a signal, but that do not have enough confidence to qualify as a probable astrophysical event.

A change in the LIGO-Virgo procedures relaxes the standards for what the collaboration calls an event and for what will disclose in real time. Miller says that this could be good for the rest of the astronomy community. "It means that there will be more chances for them to do follow-ups."

The team rushed to finish up this work so that it could focus its energy on the third observing run, due to start in March 2019, van den Brand says. Since September 2017, the three detectors have been under construction for upgrades that should roughly double their overall sensitivity. This means that the volume they monitor—and the frequency of their detections—should increase by a factor of eight.

—Davide Castelvecchi

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Scientists at LIGO have spotted more gravitational waves.

DAVID RYDER *GETTY IMAGES*

“Schrödinger’s Bacterium” Could Be a Quantum Biology Milestone

A recent experiment may have placed living organisms in a state of quantum entanglement

By Jonathan O'Callaghan

MARK GARLICK *GETTY IMAGES*

An artist's concept of quantum entanglement between two atoms.

Jonathan O'Callaghan is a freelance space and science journalist based in London. You can follow him on Twitter @Astro_Jonny.

The quantum world is a weird one. In theory and to some extent in practice its tenets demand that a particle can appear to be in two places at once—a paradoxical phenomenon known as superposition—and that two particles can become "entangled," sharing information across arbitrarily large distances through some still-unknown mechanism.

Perhaps the most famous example of quantum weirdness is Schrödinger's cat, a thought experiment devised by Erwin Schrödinger in 1935. The Austrian physicist imagined how a cat placed in a box with a potentially lethal radioactive substance could, per the odd laws of quantum mechanics, exist in a superposition of being both dead and alive—at least until the box is opened and its contents observed.

As far-out as that seems, the concept has been experimentally validated countless times on quantum scales. Scaled up to our seemingly simpler and certainly more intuitive macroscopic world, however, things change. No one has ever witnessed a star, a planet or a cat in superposition or a state of quantum entanglement. But ever since quantum theory's initial formulation in the early 20th century, scientists have wondered where exactly the microscopic and macroscopic worlds cross over. Just how big can the quantum realm be, and could it ever be big enough for its weirdest aspects to intimately, clearly influence living things? Across the past two decades the emergent field of quantum biology has sought answers for such questions, proposing and performing experiments on living organisms that could probe the limits of quantum theory.

Those experiments have already yielded tantalizing but inconclusive results. Earlier this year, for example, researchers showed the process of photosynthesis—whereby organisms make food using light—may involve some quantum effects. How birds navigate or how we smell also suggest quantum effects may take place in unusual ways within living things. But these only dip a toe into the quantum world. So far, no one has ever managed to coax an entire living organism—not even a single-celled bacterium—into displaying quantum effects such as entanglement or superposition.

So a new paper from a group at the University of Oxford is now raising some eyebrows for its claims of the successful entanglement of bacteria with photons—particles of light. Led by the quantum physicist Chiara Marletto and published in October in the *Journal of Physics Communications*, the study is an analysis of an experiment conducted in 2016 by David Coles from the University of Sheffield and his colleagues. In that experiment Coles and company sequestered several hundred photosynthetic green sulfur bacteria between two mirrors, progressively shrinking the gap between the mirrors down to a few hundred nanometers—less than the width of a human hair. By bouncing white light between the mirrors, the researchers hoped to cause the photosynthetic molecules within the bacteria to couple—or interact—with the cavity, essentially meaning the bacteria would continuously absorb, emit and reabsorb the bouncing photons. The experiment was successful; up to six bacteria did appear to couple in this manner.

Marletto and her colleagues argue the bacteria did more than just couple with the cavity, though. In their analysis they demonstrate the energy signature produced in the experiment could be consistent with the bacteria's photosynthetic systems becoming entangled with the light inside the cavity. In essence, it appears certain photons were simultaneously hitting and missing photosynthetic molecules within the bacteria—a hallmark of entanglement. "Our models show that this phenomenon being recorded is a signature of entanglement between light and certain degrees of freedom inside the bacteria," she says.

According to study co-author Tristan Farrow, also of Oxford, this is the first time such an effect has been glimpsed in a living organism. "It certainly is key to demonstrating that we are some way toward the idea of a 'Schrödinger's bacterium,' if you will," he says. And it hints at another potential instance of naturally emerging quantum biology: Green sulfur bacteria reside in the deep ocean where the scarcity of life-giving light might even spur quantum-mechanical evolutionary adaptations to boost photosynthesis.

There are many caveats to such controversial claims, however. First and foremost, the evidence for entanglement in this experiment is circumstantial, dependent on how one chooses to interpret the light trickling through and out of the cavity-confined bacteria. Marletto and her colleagues acknowledge a classical model free of quantum effects could also account for the experiment's results. But, of course, photons are not classical at all—they are quantum. And yet a more realistic "semiclassical" model using Newton's laws for the bacteria and quantum ones for photons fails to reproduce the actual outcome Coles and his colleagues observed in their laboratory. This hints that quantum effects were at play in both the light and the bacteria. "It's a little bit indirect, but I think it's because they're only trying to be so rigorous in ruling out things and claiming anything too much," says James Wootton, a quantum computing researcher at IBM Zurich Research Laboratory who was not involved in either paper.

The other caveat: the energies of the bacteria and the photon were measured collectively, not independently. This, according to Simon Gröblacher of Delft University of Technology in the Netherlands who was not part of this research, is somewhat of a limitation. "There seems to be something quantum going on," he says. "But...usually if we demonstrate entanglement, you have to measure the two systems independently" to confirm any quantum correlation between them is genuine.

Despite these uncertainties, for many experts, quantum biology's transition from theoretical dream to tangible reality is a question of when, not if. In isolation and collectively, molecules outside of biological systems have already exhibited quantum effects in decades' worth of laboratory experiments, so seeking out these effects for similar molecules inside a bacterium or even our own bodies would seem sensible enough. In humans and other large multicellular organisms, however, such molecular quantum effects should be averaged out to insignificance—but their meaningful manifestation within far smaller bacteria would not be too shocking. "I'm a little torn about how surprising [this finding] is," Gröblacher says. "But it's obviously exciting if you can show this in a real biological system."

Several research groups, including those led by Gröblacher and Farrow, are hoping to take these ideas even further. Gröblacher has designed an experiment that could place a tiny aquatic animal called a tardigrade in superposition—a proposition much more difficult than entangling bacteria with light owing to a tardigrade's hundreds-fold-larger size. Farrow is looking at ways to improve on the bacterial experiment; this year he and his colleagues hope to entangle two bacteria together, rather than independently with light. "The long-term goals are foundational and fundamental," Farrow says. "This is about understanding the nature of reality, and whether quantum effects have a utility in biological functions. At the root of things, everything is quantum," he adds, with the big question being whether quantum effects play a role in how living things work.

It might be, for example, that "natural selection has come up with ways for living systems to naturally exploit quantum phenomena," Marletto notes, such as the aforementioned example of bacteria photosynthesizing in the light-starved deep sea. But getting to the bottom of this requires starting small. The research has steadily been climbing toward macrolevel experiments, with one recent experiment successfully entangling millions of atoms. Proving the molecules that make up living things exhibit meaningful quantum effects—even if for trivial purposes—would be a key next step. By exploring this quantum-classical boundary, scientists could get closer to understanding what it would mean to be macroscopically quantum, if such an idea is true.

An artist's rendition of NASA's InSight lander moments before its successful touchdown on the Martian surface.

NASA's InSight Mission

After enduring a high-tension descent from orbit, the spacecraft will now begin its quest to peel back the profound mysteries of the Red Planet's interior

By Ian O'Neill

JPL-CALTECH AND NASA

A new space robot now calls Mars "home."

NASA's InSight lander completed its seven-month interplanetary journey of nearly 500 million kilometers in dramatic style on November 26, 2018 slamming into the Martian atmosphere at a speed of nearly 20,000 kilometers per hour. Only six-and-a-half harrowing minutes later, after ejecting its heatshield, deploying a supersonic parachute and firing retrorockets, its speed had dramatically slowed to a jogging pace after traversing the 130 kilometers between Mars's upper atmosphere and the planet's arid surface.

According to mission controllers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, InSight's entry, descent and landing (EDL) phase was completed without a hitch and the $850 million lander touched down shortly after 2:50 P.M., Eastern time. The mission's twin relay CubeSat companions, Mars Cube One (MarCO), which have been flying alongside InSight during its interplanetary cruise phase, also successfully fulfilled their mission, transmitting signals from Mars during InSight's EDL back to Earth in near real-time. Minutes after landing, InSight transmitted its first color image from Mars, via the MarCO relay, showing a bleak landscape through a veneer of dust that had accumulated on its camera's protective cover. Now that the dust has settled, NASA can focus on the lander's future as a scientific gold mine that will give Mars an unprecedented internal examination to better understand heretofore hidden details of the world's origins and history.

The lander safely touched down on its dusty landing site of Elysium Planitia, near the Red Planet's equator, a region scientists refer to as "vanilla"—not because it is boring per se but because it is flat and free of rocky obstacles that could damage the lander. And besides, InSight cares little for the superficialities on the surface; its interest lies far deeper.

InSight, which stands for "Interior Exploration using Seismic Investigations, Geodesy and Heat Transport," is a stationary science platform with a suite of instrumentation that will work in concert to give the planet an "ultrasound." Unlike its more mobile brethren, such as NASA's Curiosity and Opportunity rovers, it will do all of its investigations where it landed, in situ. Its ultra-sensitive seismometer (Seismic Experiment for Interior Structure, or SEIS, experiment) will detect seismic waves rippling through Mars and, by measuring their propagation through the subsurface, will assemble a detailed picture of Mars's interior for the first time. Using its robotic arm, InSight will pluck SEIS from the lander's top deck to place it carefully on the dusty surface. Another instrument (the Heat Flow and Physical Properties Package, or HP3, experiment) will also be placed on the surface, deploying a thermal probe that will drill itself several meters into the surface to measure heat percolating through the planet. InSight also has an experiment (Rotation and Interior Structure Experiment, or RISE) that will precisely measure the planet's "wobble" to reveal the size and density of the Martian core.

Until now, all Mars missions have focused on the planet's surface and atmosphere. Although InSight will also have an onboard weather station and suite of cameras, the mission's focus is on peeling back the profound mysteries of the Martian interior.

"The main goal of InSight is to understand what the fundamental makeup is of Mars, as in how large the core is, how large the mantle is and how large the crust is," says Tom Hoffman, project manager for InSight at JPL. "We're doing that largely with a seismometer detecting 'marsquakes.'"

Quakes are a familiar feature of our tectonically active Earth. Continental plates shift as they float atop a hot and viscous mantle, rubbing and pushing against one another, producing earthquakes and volcanoes. Mars, however, is very different. It is not currently tectonically active, and its volcanoes have been dormant for hundreds of millions of years. Unlike earthquakes, marsquakes are a consequence of a cooling and shrinking world, says Hoffman, and hopes are high that there will be many marsquakes for InSight to detect. The seismic waves marsquakes produce will be used by InSight to create a 3-D picture of Mars's interior—but they can also be used to study meteorites thudding into the surface.

"Depending on how large the meteorite impacts are and how far away they are from the lander, it determines how well we can detect them or not," adds Hoffman. "We also have orbital assets [such as NASA's Mars Reconnaissance Orbiter] that can then show us exactly where that impact was, because we are constantly mapping the surface."

Interestingly, meteorite impacts also had an important part to play in the selection of Elysium Planitia as InSight's landing zone, says Suzanne Smrekar, InSight deputy principal investigator, who is also at JPL. Once deployed on the surface, the HP3 self-penetrating heat flow probe—aptly nicknamed "the mole"—will pound the ground tens of thousands of times to eventually burrow as much as 5 meters below the surface. But it can only do so if there is no hard bedrock in its way. How, though, could scientists know whether or not there are mission-scuttling rocks hidden just below Elysium Planitia's dirt?

"An impact crater can act like a probe of the subsurface," Smrekar explains. While surveying the landing site during the planning phase of InSight's mission, scientists studied the ejecta from small impact craters scattered across Elysium Planitia. As a rule, meteors will gouge a hole approximately a tenth as deep as the crater's diameter. They found that, for this region, craters as wide as 100 meters didn't appear to throw up any large rocks, meaning the upper 10 meters of this region is composed mainly of fine material, such as small stones, sandy material and dust, that would pose no insurmountable barriers for InSight's "mole."

Assuming the heat flow probe deploys successfully, the measurements it makes could transform our understanding not only of how Mars evolved, but also how other rocky planets, like Earth, came to be.

After formation, planets contain a lot of heat that slowly leaks to the surface over billions of years. Directly measuring the flow of this heat in modern Mars will help alleviate some huge uncertainties in planetary formation models. For example, planets form by slowly accreting asteroids, but the type of asteroid that clumps together greatly affects a planet's composition and therefore its heat flow. Many indirect measurements of Mars's heat flow have been made, but they often contradict theoretical models.

"We'll be able to track the location of InSight to an accuracy of about 10 inches. That's phenomenal—it's as close as you can get to magic and still be science."
—Bruce Banerdt

"Some heat flow estimates are consistent with the idea that Mars, and all the rocky planets in fact, formed from a certain class of asteroids—chondritic asteroids—that have a certain amount of radiogenic material [which generates heat]," explains Smrekar. "But some of those measurements don't agree with that; they indicate that Mars is composed of less chondritic material and its interior should be a lot colder than our models predict."

Once InSight measures the heat flow number just below its landing site, it can be extrapolated globally, adds Smrekar. "This one crazy number will tell us so much about the history of Mars as well as the present day—that's what I'm most excited to get."

Beyond developing planetary evolution models, the heat flow measurements will also have implications for understanding if Mars has ever been habitable enough to support life. Some hypotheses suggest that there may be reservoirs of water just below the Martian surface, and the value of the heat flow number could help us understand whether these reservoirs are in a life-giving liquid state or are a not-so-life-giving solid ice.

InSight has another trick to decipher what's inside Mars, but it needs a little help from the Deep Space Network (DSN)—radio antennae on Earth that maintain contact with robotic space missions throughout the solar system. By analyzing subtle frequency shifts in radio transmissions between InSight and the DSN, scientists will be able to measure just how fast the lander is moving relative to Earth. Over the two years of InSight's primary mission, the experiment will build a picture of how much Mars wobbles as it rotates, using the lander as a fixed point on the planet's surface.

"We'll be able to track the location of InSight to an accuracy of about 10 inches," says Bruce Banerdt, InSight principal investigator. "That's phenomenal—it's as close as you can get to magic and still be science."

Mars's wobble can provide us with information about the core of the planet, says Banerdt. "If Mars's core is liquid, it's actually kinda sloshing around inside, and the size and speed of that wobble is related to the size of the core and the density of the core. The heavier the core, the more sloshing, the greater the effect on the wobble."

InSight will be very different from the Mars missions that have come before it, but it's going to fill a crucial role in humanity's quest to understand how Mars formed and whether it has ever played host to life. Ultimately, by giving Mars an internal examination we'll be able to compare the Red Planet's composition with Earth's, greatly improving our understanding of how planets in our solar system—and even exoplanets orbiting other stars—actually form.

Finding Alien Life May Require Giant Telescopes Built in Orbit

Scientific American **reports on new efforts from NASA and other federal agencies seeking to service and assemble large structures—such as life-finding telescopes—in space**

By Lee Billings

Astronauts repair and upgrade the Hubble Space Telescope during the first servicing mission to that orbital observatory, in 1993. NASA is now studying how telescopes far larger than Hubble might someday be assembled and serviced in space by astronauts or robots.

NASA

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

AFTER SNAPPING THE FINAL PIECE INTO PLACE WITH A SATISFYING "CLICK" SHE FEELS through her spacesuit gloves, the astronaut pauses to appreciate the view. Her reflection swims before her in a silvery disk the size of three tennis courts; for a moment she feels like a bug floating on a darkened pond. Composed of hundreds of interlocking metallic hexagons like the one she has just installed, the disk is a colossal mirror 30 meters wide, the starlight-gathering eye of the largest space telescope ever built. From her perch on the robotic arm of a small space station, Earth is a tiny blue and white orb she could cover with an outstretched thumb, dwarfed by the bright and silent moon spinning thousands of kilometers below her feet.

Although this scene remains the stuff of science fiction, an ad hoc assemblage of scientists, engineers and technocrats now say it is well on its way to becoming reality. Under the auspices of a modest NASA-sponsored initiative, this diverse group is gauging how the space agency might build bigger, better space telescopes than previously thought possible—by constructing and servicing them in space. The effort, formally known as the "in-Space Assembled Telescope" study (iSAT), is part of a long trend in which science advances by piggybacking on technologies created for more practical concerns.

For example, the development of surveillance satellites and warhead-carrying rockets during the 20th-century cold war also catalyzed the creation of robotic interplanetary probes and even NASA's crewed *Apollo* lunar missions. Similarly, in the 21st century a soaring military and industrial demand for building and servicing satellites in orbit could lead to dramatically enhanced space telescopes capable of definitively answering some of science's biggest questions—such as whether or not we are alone. "The iSAT is a program that can be NASA's next *Apollo*," says study member Matt Greenhouse, an astrophysicist at the space agency's Goddard Space Flight Center. "And the science enabled by the iSAT would likely include discovery of extraterrestrial life—an achievement that would eclipse *Apollo* in terms of impact on humanity."

READY FOR PRIME TIME

In some respects, building and repairing spacecraft in space is a revolution that has already arrived, merely kept under the radar by a near-flawless track record that makes it seem deceptively routine. Two of NASA's pinnacle projects—the International Space Station (ISS) and the Hubble Space Telescope—owe their existence to orbital construction work. Assembled and resupplied in orbit over two decades, the ISS is now roughly as big as a football field and has more living space than a standard six-bedroom house. And only space-based repairs allowed Hubble to become the world's most iconic and successful telescope, after a space shuttle crew on a first-of-its-kind servicing mission in 1993 fixed a crippling defect in the observatory's primary mirror. Astronauts have since conducted four more Hubble servicing missions, replacing equipment and upgrading instruments to leave behind an observatory reborn.

Today multiple projects are carrying the momentum forward from those pioneering efforts, cultivating powerful new capabilities. Already NASA and the Pentagon's Defense Advanced Research Projects Agency (DARPA) as well as private-sector companies such as Northrop Grumman and Space Systems Loral (SSL) are building robotic spacecraft for launch in the next few years on lengthy missions to refuel, repair, re-position and upgrade governmental and commercial satellites. Those spacecraft—or at least the technologies they demonstrate—could also be used to assemble telescopes and other large structures in space such as those associated with NASA's perennial planning for human missions to the moon and Mars. In 2017—under the auspices of a "partnership forum" between NASA, the U.S. Air Force and National Reconnaissance Office—the space agency took the lead on crafting a national strategy for further public and private development of in-space assembly in the 2020s and beyond.

These trends could end what some experts see as a "dark age" in space science and exploration. "Imagine a world where once your car runs low on fuel, instead of driving to the gas station you take it to the junkyard and abandon it. Imagine a world where once you've moved into your house for the first time you have no way of ever getting more groceries inside, having a plumber come to fix a leaky pipe or any way to bring in and install a new TV. Imagine a world where we all live in tents that we can carry on our backs and no one thinks to build anything larger or more permanent. That seems crazy, doesn't it?" says iSAT study member Joe Parrish, a program manager for DARPA's Tactical Technology Office who helms its Robotic Servicing of Geosynchronous Satellites (RSGS) mission. "But that's exactly the world we live in right now with our $1-billion-class assets in space.... I think we will look back on the era before on-orbit servicing and assembly the way we now look back on the era when leeches were used to treat diseases."

BIGGER *IS* BETTER

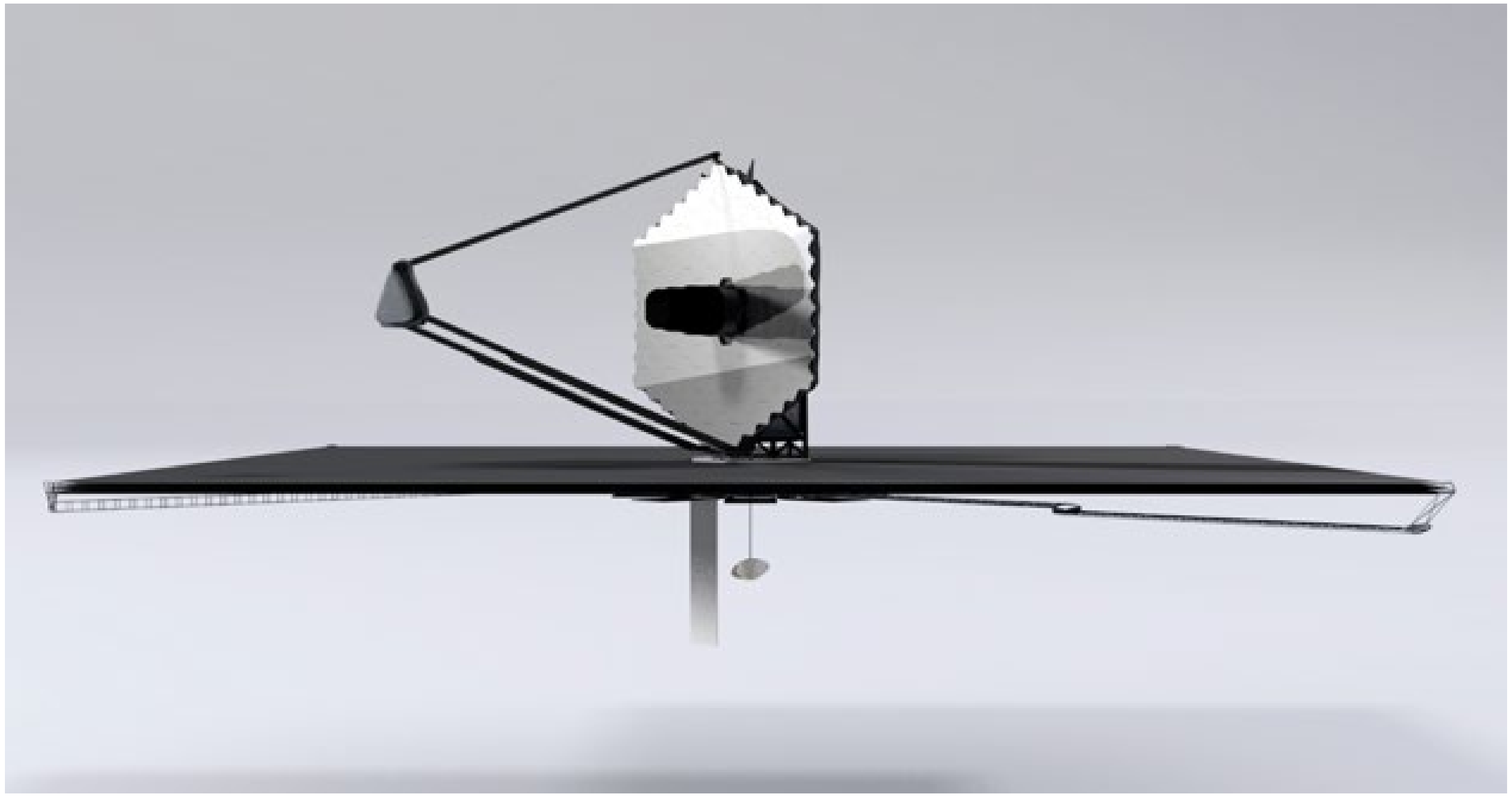
The fundamental reality behind the push for in-space assembly is easy to understand: Anything going to space must fit within the rocket taking it there. Even the very biggest—the mammoth 10-meter rocket fairing of NASA's still-in-development Space Launch System (SLS)—would be unable to hold something like the ISS or even the space agency's smaller "Gateway," a moon-orbiting space station proposed for the 2020s. Launching such megaprojects piece by piece, for orbital assembly by astronauts or robots, is literally the only way to get them off the ground. And coincidentally, even though massive "heavy lift" rockets such as the SLS remain ruinously expensive, the midsize rockets that could support orbital assembly with multiple launches are getting cheaper all the time.

An artist's rendition of the upcoming Dragonfly mission, a collaboration between NASA and Space Systems Loral to demonstrate technologies required for orbital construction. Dragonfly's robotic arm (*inset*) will assemble and deploy reflectors to create a large radio antenna when the mission launches sometime in the 2020s.

NASA AND SSL

The forces demanding supersize space telescopes are straightforward, too: The larger a scope's light-collecting mirror is, the deeper and finer its cosmic gaze. Simply put, bigger is better when it comes to telescopes—especially ones with transformative objectives such as tracking the coalescence of galaxies, stars and planets throughout the universe's 13.8-billion-year history, learning the nature of dark matter and dark energy, and seeking out signs of life on habitable worlds orbiting other stars. Most of today's designs for space telescopes pursuing such alluring quarry cap out with mirrors as wide as 15 meters—but only because that is the approximate limit of what could be folded to fit within a heavy-lift rocket like the SLS.

Astronomers have long fantasized about building



An artist's rendition of the Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR), a concept for a future life-finding space telescope under investigation by NASA. The largest version of LUVOIR would boast a primary mirror 15 meters wide, bringing it to the limit of what could fit within the world's largest rockets.

NASA AND GSFC

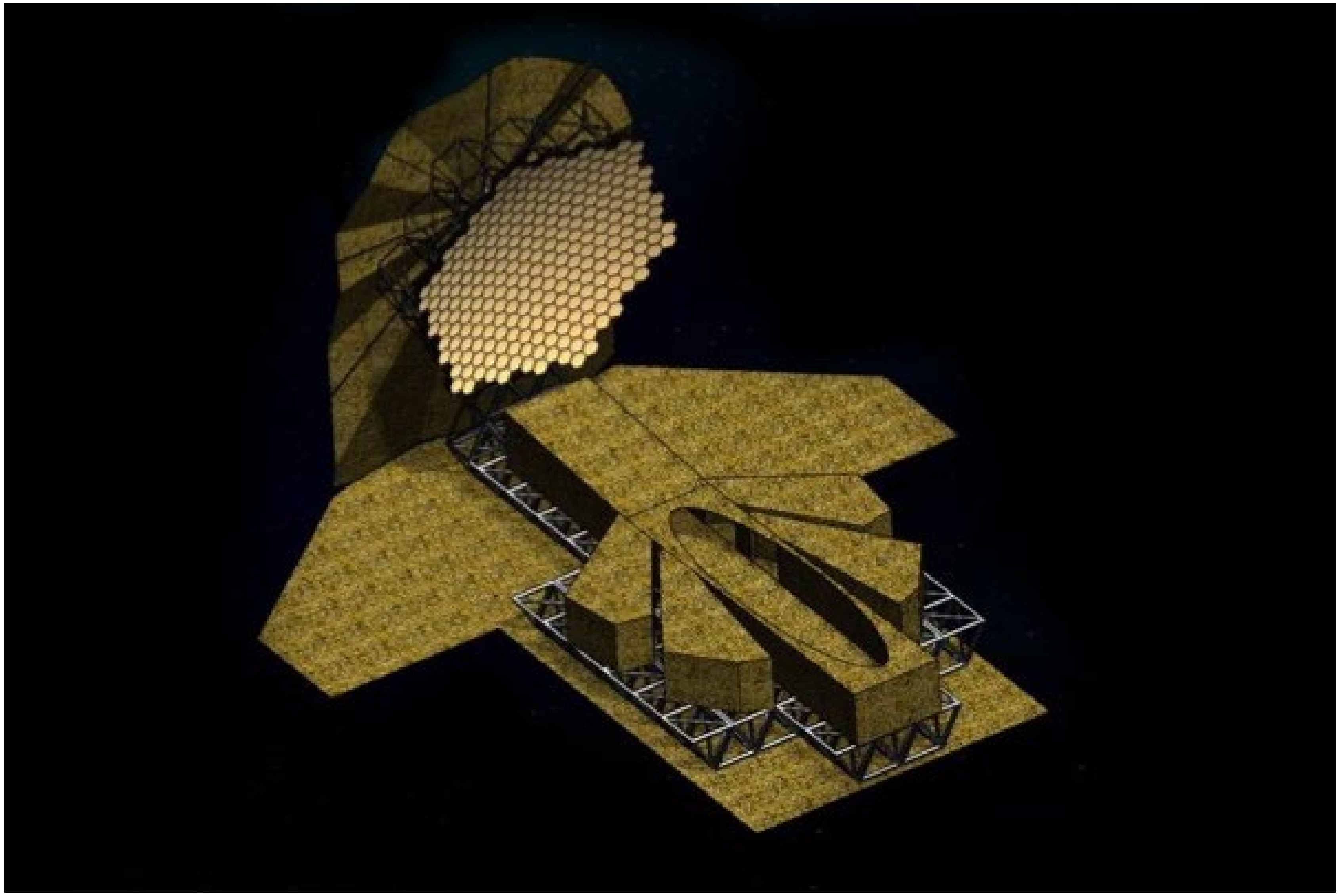
space observatories even bigger, with mirrors 30 meters wide or more—rivaling the sizes of ground-based telescopes already under construction for the 2020s. Assembled far above our planet's starlight-scattering atmosphere, these behemoths could perform feats the likes of which ground-based observers can only dream, such as taking pictures of potentially Earth-like worlds around a huge sample of other stars to determine whether those worlds are actually habitable—or even inhabited. If our own Earth is any example to go by, life is a planetary phenomenon that can transform the atmosphere and surface of its home world in clearly recognizable ways; provided, that is, one has a telescope big enough to see such details across interstellar distances.

A recent "Exoplanet Science Strategy" report from the National Academies of Sciences, Engineering and Medicine said NASA should take the lead on a major new space telescope that begins to approach that grand vision—something capable of surveying hundreds (or at least dozens) of nearby stars for snapshots of potential exo-Earths. That recommendation (itself an echo from several previous prestigious studies) is reinforced by the core conclusion of another new Academies report which calls for the agency to make the search for alien life a more fundamental part of its future space exploration activities. These reports build on the growing consensus that our galaxy likely holds billions of potentially habitable worlds, courtesy of statistics from NASA's recently deceased Kepler space telescope and the space agency's newly launched Transiting Exoplanet Survey Satellite. Whether viewed through the lens of scientific progress, technological capability or public interest, the case for building a life-finding space telescope is stronger than ever before—and steadily strengthening. Sooner or later it seems NASA will find itself tasked with making this longed-for giant leap in the search for life among the stars.

How big such a telescope must be to offer a reasonable chance of success in that interstellar quest depends on life's still-unknown cosmic prevalence. With a bit of luck, one with a four-meter mirror might suffice to hit the jackpot, locating an inhabited exo-Earth around one of our sun's nearest neighboring stars. But if the cosmos is less kind and the closest life-bearing worlds are much farther away, something in excess of the 15-meter limit imposed by near-future rockets could be necessary to sniff out any living planets within our solar system's corner of the galaxy. In short, in-space assembly may offer the only viable path to completing the millennia-long effort to end humanity's cosmic loneliness.

DECADAL DREAMS

"Scientists have already hit a design constraint to achieve the science they want to advance," says Nick Siegler, an astrophysicist at NASA's Jet Propulsion Laboratory (JPL) and chief technologist of the space agency's Exoplanet Exploration Program. "What if that particular constraint did not exist? This is what in-space assembly offers—the opportunity to push the boundaries, both in scientific discoveries and human exploration." Along with Harley Thronson, a senior scientist at NASA Goddard, and Rudra Mukherjee, a JPL roboticist, Siegler formed what would become the Future Assembly and Servicing Study Team (FASST) in late 2016, organizing the group's inaugural meeting at an astrophysics conference in Texas in early 2017.



A schematic illustration of the iSAT study's "proof of concept" design, a hypothetical telescope with a 20-meter mirror designed for space-based robotic assembly and servicing. A starlight-blocking, telescope-cooling "sunshade" is shown behind the honeycomb-like segmented primary mirror as well as beneath the truss-mounted instrument bay. Such an observatory could be built in increments, progressively increasing in capability as new instruments and additional primary mirror segments are launched from Earth and installed.

The iSAT study is the first NASA-funded FASST activity, but probably not the last. The team aims to be more than just another group of cloistered academics proffering pie-in-the-sky ideas. Its membership includes level-headed spaceflight veterans such as John Grunsfeld, a former astronaut and head of NASA's science programs who served as an orbital repairman on three of the five Hubble servicing missions. The team's intention, Grunsfeld and other participants say, is less to persuade the space agency to champion in-space telescope assembly, and more to clarify the approach's potential benefits and drawbacks. "Assembly of telescopes in space will clearly yield bigger telescopes, but answers to the why, what, how, risk, cost and when to do in-space assembly do not yet exist," says team member Ron Polidan, a now-retired expert in space technology development at NASA and Northrop.

What is already certain, though, is time is running out for the group to have a meaningful impact on NASA's near-future plans. The team is now conducting frequent teleconferences, sprinting to complete a "proof of concept" study examining the in-space assembly of a hypothetical telescope with a 20-meter mirror. What would such a telescope's modular components be, where in space would it be built and operated, which rockets and spacecraft would support it and how many launches would be required? Would the telescope's pieces be assembled by astronauts or by robots? And, perhaps most importantly, could in-space assembly become a cost-competitive approach to building smaller space telescopes that would otherwise follow the tradition of being stowed and deployed from a single rocket? The iSAT team's report will address such questions when it appears in the spring of next year.

That timing is important for potentially influencing the final design of NASA's proposed lunar Gateway, which could be used as a deep-space construction platform. The iSAT study's timing also overlaps with the onset of the astrophysics "Decadal Survey," a once-every-10-year process in which the U.S. research community creates a prioritized list of recommended future projects for NASA and Congress to follow. The Decadal Survey's most impactful recommendation would be a multibillion-dollar space telescope for the 2030s—a "flagship" project, the largest class of science mission the space agency undertakes.

Four NASA-sponsored Science and Technology Definition Team (STDT) studies are presently underway in anticipation of the Decadal Survey, each developing a unique flagship concept and associated suite of science objectives based on scientific, technological and budgetary considerations. According to Siegler and other NASA officials, the largest designs from two of the four STDT

NASA, JPL-CALTECH AND R. MUKHERJEE ET AL.

studies—both with exoplanet-imaging as a foremost goal—have already reached either the size or weight limitations of the most powerful version of NASA's nascent SLS heavy-lift rocket. But as of yet none of the four studies have incorporated meaningful considerations of in-space assembly techniques.

Siegler, for one, is not surprised. "The STDTs are all doing a great job coming up with compelling science while also trying to minimize their mission cost," he says. "[In-space assembly] has not yet shown how it can reduce cost, and from their perspective it may appear as an increase in complexity. The onus is on our study to show where the benefits are, if they actually exist."

Polidan offers a blunter assessment. "A few community members have suggested to me personally that we wait and do the iSAT study until after the Decadal Survey," he says. "All these comments are due to the current lack of a detailed definition of assembling telescopes in space, and a fear that it will look 'too good,' and somehow influence the Decadal committee to go down a path that is too risky or too costly for astrophysics."

The James Webb Space Telescope's scientific instruments and optical elements—including its gold-plated 6.5-meter primary mirror—emerge from cryogenic testing at NASA's Johnson Space Center in Houston on December 1, 2017.

NASA

WEBB'S CAUTIONARY TALE

A new very large space telescope might be a hard sell for many in the U.S. astrophysics community, regardless of whether it is built on the ground or in space. Either approach could prove a bridge too far for NASA, based on the space agency's problem-plagued flagship next in line to launch: the James Webb Space Telescope, which seeks to glimpse the universe's very first stars and galaxies. "People are still traumatized by what happened with Webb, and rightfully so—they are worried that something similar will happen again," says Scott Gaudi, an astronomer at The Ohio State University and co-author of the "Exoplanet Science Strategy" report.

The project hinges on the nail-biting self-deployment of a foldable 6.5-meter mirror and an even larger "sunshield"—each the largest ever launched—as the observatory travels to a dark, quiet point past the moon and beyond ready repair or servicing by NASA's astronaut corps. Ensuring all will go as planned has proved enormously expensive. From a notional projected budget of $1.6 billion in 1996 and a potential launch date as early as 2007, Webb's actual price tag has ballooned to nearly $10 billion, and the telescope's launch is now slated for no earlier than 2021. The funds to pay for Webb's overruns have come in part from cannibalizing many other worthy projects, to the overall detriment of NASA's space-science portfolio and near-universal consternation of researchers.

"Going into the Decadal Survey, my fear is that the Decadal committee will be so frightened of cost that they won't recommend any flagship," says one prominent astrophysicist who asked to remain anonymous. "And if the Decadal—the community, really—is too shy and doesn't recommend a large strategic mission, then it becomes a self-fulfilling prophecy that there simply will not be one." That, in turn, could lead to the U.S. ceding its preeminence in the field of space-based astronomy to competing nations, namely China, which has plans of its own for in-space assembly—including taikonaut-tended orbital observatories. The resulting exodus of scientists and engineers for fairer international shores could devastate U.S. space science for generations, with far-reaching consequences for the nation's continuance as a global superpower.

"A DAMN GOOD REASON TO DO IT"

Whether all this makes Webb a testament for or against in-space assembly and servicing is a matter of debate. Any hiccups in the mirror's or sunshield's postlaunch deployments could render Webb a $10-billion hunk of inoperative space junk—and that assumes, of course, the telescope escapes Earth at all rather than falling victim to an unlikely-but-possible malfunction of its launch vehicle. In principle, building and testing the telescope in orbit could have reduced or nullified these and other threats—albeit potentially with a greater price tag. "In-space assembly would have completely relieved the requirement to fold and deploy Webb, and furthermore, a launch failure would not necessarily be a mission failure," Siegler notes.

And even if all goes as planned with Webb, it has not been designed with servicing in mind (unlike its predecessor Hubble—or, for that matter, its successor, a planned post-Webb flagship called WFIRST). Within about a decade of reaching its deep-space destination Webb will run out of fuel, presumably sealing its space-junk fate. "That is astonishing," says iSAT study member Gordon Roesler, the former head of DARPA's RSGS program. "Wouldn't it be nice if Webb could last a lot longer? The general thinking of [iSAT] is that something like Webb makes more sense as a 50-year mission, where we can plan from the outset to visit it, replenish consumables, replace parts and install new instruments with better technology."

For all those reasons, despite Webb's status as the premier facility for space-based astronomy in the 2020s and its associated wealth of new technologies that can feed in to even more advanced future observatories, many iSAT team members team see the project as an unsustainable "evolutionary dead end" whose time has in some respects already passed. Whatever arises from its fantastic-but-flawed legacy will depend not only on the outcomes of the iSAT study and the Decadal Survey, but also on the courage of scientists and policy makers to embrace bold, paradigm-shifting new approaches.

"The scientific community is sometimes its own worst enemy when it comes to understanding what it is that's possible," says Ken Sembach, director of the Space Telescope Science Institute. "Some of us now have the preconceived idea that it is not possible to build another telescope that is bigger and, yes, maybe more expensive than Webb. But I talk all the time to younger researchers, Congress and the public, and they all ask, 'Why aren't we thinking bigger?' People want to support ambitious things. So it is possible—provided there is a damn good reason to do it."

These Dusty Young Stars Are Changing the Rules of Planet-Building

Astronomers peer inside planetary nurseries for clues about how our solar system and others came to be

By Rebecca Boyle

An artist's impression of a planetary nursery, in which growing planets etch rings in the disk of dust and gas around a young star.

ESO/L. Calçada

Rebecca Boyle is an award-winning freelance journalist based in St. Louis, Mo. She is a contributing writer for the *Atlantic*, and her work regularly appears in *New Scientist*, *Wired*, *Popular Science* and other publications and has been anthologized in the *Best American Science* and *Nature Writing* series.

SOME 100,000 YEARS AGO, WHEN NEANDERTALS STILL OCCUPIED the caves of southern Europe, a star was born. It appeared when a ball of gas collapsed and ignited within a stellar factory known as the Taurus Molecular Cloud. Then, leftover material began to cool and coalesce around it, forming dust grains and a hazy envelope of gas.

In September 2014, some of the light from that hot young star and its surroundings landed inside 66 silvery parabolas perched on a plateau in Chile's Atacama Desert—the driest on Earth. The photons had taken 450 years to make the journey. Astronomers were waiting. They were conducting a test of the Atacama Large Millimeter/submillimeter Array (ALMA), which features radio antennas separated by distances of up to 15 kilometers. With such long spans between them, the antennas work as a high-resolution receiver that can discern cool objects less than a millimeter across.

When the telescope team trained ALMA on the young star, named HL Tauri, they expected to see a bright smear of dust and gas. Instead, when ALMA's supercomputer stitched together those photons, the image resolved into a disk with a well-defined ring structure, with gaps seemingly etched by small, infant planets orbiting a central star. It looked like a furry, orange Saturn. It looked like nothing astronomers had ever seen.

"I kept flipping through their paper, and I was like, 'Where is the real image? This is obviously a model,'" says Kate Follette, an astronomer at Amherst College in Massachusetts.

What the researchers had captured was a picture of a planetary nursery—where baby planets were forming in a disk of gas and dust around HL Tauri. This observation marked the start of a revolution in the burgeoning field of planetary-disk imaging. In the four years since, astronomers have captured "baby pictures" of numerous other systems. These planet-forming regions exhibit a wide variety of patterns. Some are neat ovals, with lanes as clearly defined as those of a race track. Others look like galaxies in miniature, with swirling arms that branch off into open arcs.

The latest observations, including results announced in April and July, have revealed planets in the process of being sculpted, with dust and gas flowing onto bulbous, red-hot infant worlds.

But as the menagerie of young planetary systems grows, researchers are struggling to square their observations with current theories on how our solar system and others formed. Such ideas have been in turmoil ever since astronomers started discovering planets around distant stars—a list that now numbers in the thousands. The solar system has rocky planets near the sun and giant gas balls farther out, but the panoply of exoplanets obeys no tidy patterns. And the rule book for world-building is getting more complicated as researchers find evidence of planets in the process of being born. Still, astronomers hope that witnessing such birth pangs will shed light on how all planetary systems, including our own, came to be. "We see all kinds of structure in these disks, even at very young ages," says Follette. "Even younger than we classically thought planets should form."

COLLISIONS AND CURDLING

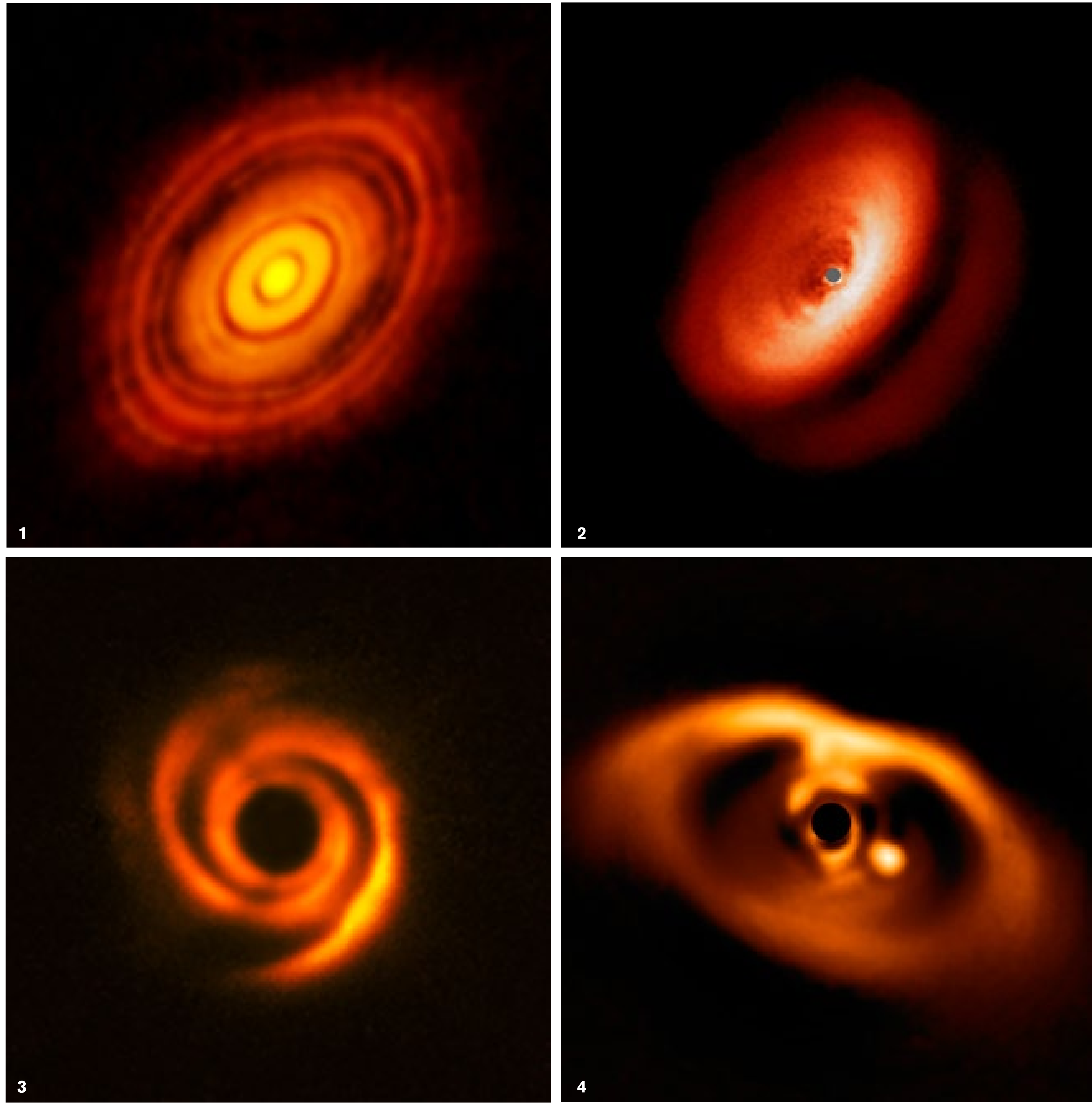
The prevailing theory of how the solar system formed goes back to the German philosopher Immanuel Kant. In 1755, he imagined the sun and planets arising from a nebulous cloud of gas and dust that slowly collapsed and flattened. Today, the widely accepted general model for how the process unfolded holds that the sun collapsed inside a molecular cloud, a star factory full of gas molecules. A ring of gas and dust would have remained after the star formed, cooling and progressively condensing into bigger grains, then into larger, asteroid-sized bodies called planetesimals, and ultimately into planets.

Theorists have been refining the particulars of the process since the 1970s, taking into account the distribution of planets in the solar system and the chemical components of meteorites—crumbs from the solar system's formation. By the early 2000s, they had settled on two distinct scenarios for making rocky planets and gas giants.

In one theory, called core accretion, rocky material violently smacks together, melts, coagulates and forms larger bodies, gradually creating protoplanets—compact embryonic worlds several thousand kilometers across. With their gravitational heft, protoplanets can attract a huge envelope of gas as they orbit through the planetary disk. This could enable them to metamorphose into the core of a giant planet, such as Jupiter; alternatively, their growth might ultimately stall at the rock-ball stage, as happened with Earth, Mars and the other terrestrial planets.

Others theorized that the solar system was forged not through violent collisions, but instead by a kind of curdling. In this scenario, called the streaming instability, gas and dust surrounding a star cool off quickly and begin drifting, becoming concentrated and collapsing under their own gravity. The centimeter-scale dust and ice in the disk forms agglomerations that grow into larger, denser bodies between 1 and 100 kilometers across. Then, through other processes, these grow into larger planetary embryos and, eventually, planets.

But neither of these ideas can quite explain the universe we see. Take Jupiter, which contains the vast majority of the material left behind from the sun's birth. Among the biggest questions is how the planet could have quickly grown a core big enough to hoover up the bulk of its mass; collisions between planetesimals would take many millions of years. But theorists reckon that the "natal disk" of dust and gas that surrounded the young sun would have disappeared 1 million to 10 million years after it formed, as gas dissipated and dust spiraled onto the star. (Compounding the problem, NASA's Juno probe



An ALMA image of gaps etched by growing planets in a disk of material surrounding the young star HL Tauri.❶
SPHERE captures a dusty disk around IM Lupi.❷
A spiraling disk around HD 135344B.❸
The glow of a gas giant around PDS 70.❹

ALMA (ESO, NAOJ and NRAO) (1) ESO/H. Avenhaus et al./DARTT-S collaboration (2) ESO, T. Stolker et al. (3) ESO/A. Müller et al. (4)

recently revealed that Jupiter's core is even bigger than expected, meaning that the formation process must have been extremely fast.) Jupiter's location is also hard to explain. Theorists have speculated since the 1970s that planets might migrate from one orbit to another as they form or jostle with other burgeoning planets.

The cracks in planet-formation theories only got worse in the mid-2000s, as discoveries of other planetary systems began rolling in. Some stars have large planets that complete their orbits in just a few days. Other planets circle their hosts at distances that make Jupiter seem like the sun's next-door neighbor. Although simulations are growing more complex as hardware and software improve, neither core-accretion nor streaming-instability models do a good job of explaining how such huge worlds are formed, and at such disparate distances from their stars.

One scenario that could account for far-out planets emerged in 2012. Astronomers Anders Johansen and Michiel Lambrechts at Lund University, Sweden, devised a variation on the core-accretion and streaming-instability scenarios. In their theory, dubbed pebble accretion, leftover star-forming material assembles as loose collections of dust and pebbles. Already-formed planetesimals swim among them, and then grow quickly by accumulating more pebbles, much as a snowball gets bigger as it rolls downhill. In this scenario, Johansen says, a planet would start out at the edges of a star's natal disk and gather up pebbles as it migrates inwards. Depending on gravitational interactions between worlds, it could end up either very close to its host star, or far removed from it. Astronomers think that Jupiter and Saturn might have undergone such a migration early in the life of the solar system.

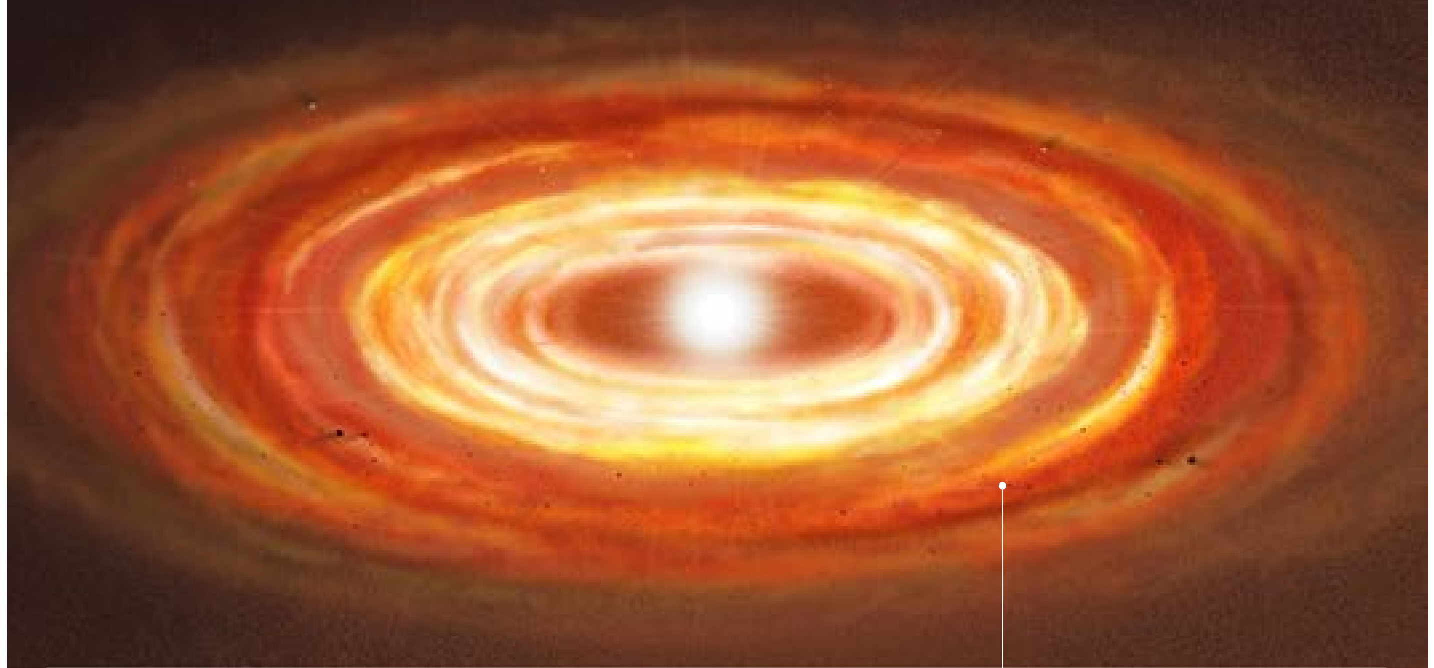
Pebble accretion has quickly gained popularity as a way of explaining systems such as HL Tauri, whose dark rings, etched in luminous dust, seem to harbor planets less than 100,000 years old. "These dark rings probably have young planets" in them, says Matthew Clement, an astronomer at the University of Oklahoma in Norman. "This has been really inspirational for us. It's confirmation, in a way, that planets grow really fast."

TALLYING IT UP

Although pebble accretion could explain how planets get big fast, it doesn't provide as much insight into how the seed of a planet—the start of the snowball—forms in the first place.

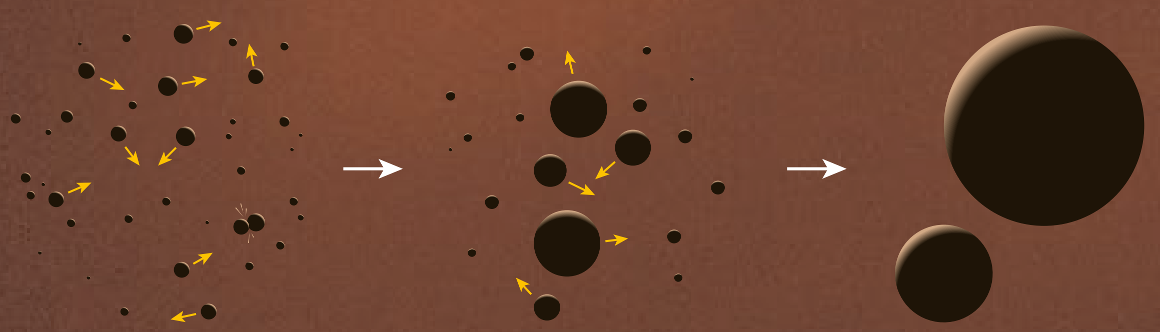
ATTRACTIVE SCENARIOS

Various theories have been proposed to explain how planets come to be. Many focus on the crucial period right after the birth of a star, when the dust and gas surrounding it somehow transform from a relatively uniform disk into planetary embryos called protoplanets—objects several thousand kilometers wide that ultimately form the cores of giant gas planets and the bulk of smaller, rocky ones.



CORE ACCRETION

In this early theory, protoplanets form through a series of violent strikes, as bits of dust and then progressively larger objects are gravitationally attracted to one another and collide—and, in many cases, merge.



NATURE

The challenge is bridging the gap between centimeter-scale bits of dust and moon-sized objects. Older simulations assumed that dust and gas moved together. “When people did this problem historically, they always assumed the dust and gas were perfectly locked to each other,” says Philip Hopkins, an astronomer at the California Institute of Technology in Pasadena.

He and Jono Squire, a postdoctoral researcher in his lab, have been revising models to separate the two, exploring complex interactions in a protoplanetary disk that can cause gas to swirl around dust grains in the same way as water eddies around sticks floating in a stream. These redirected gas flows quickly become turbulent and unstable, forcing dust to clump together like flood debris. Such modeling could help to shed light on the fundamentals of planetesimal clumping, Hopkins says. “This could really change the story.”

But as theorists tinker with accreting pebbles and swirling gas, another problem is lurking in the background. In 2013, astrophysicist Subhanjoy Mohanty of Imperial College London and astronomer Jane Greaves, now at Cardiff University, U.K., published an initial survey of protoplanetary disks in the Taurus Molecular Cloud. The observatories they used were not powerful enough to clearly resolve grooves in disks like those that ALMA saw around HL Tauri, but when the researchers tallied up how much gas and dust seemed to be present, they found that intermediate-sized stars had disks that packed much less mass than expected.

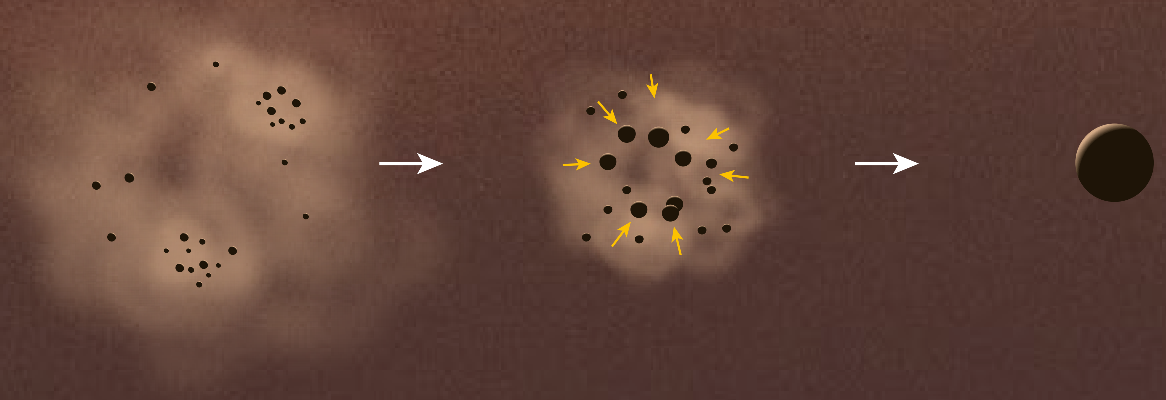
This summer, astronomer Carlo Manara at the European Southern Observatory (ESO) in Garching, Germany, took another look, and found this to be true throughout the Milky Way. Protoplanetary disks have just a fraction—sometimes as little as 1 percent—of the combined mass of exoplanets orbiting similar stars, he found. This would mean that planetary systems are bigger than the stuff used to make them.

Whatever the explanation for this seemingly impossible scenario, theorists will have to grapple with the implications. To account for exoplanet observations, they have generally started with vast quantities of material. “You need a huge amount of mass in the disk [for it] to exert gravity on itself to act like a seed, and collapse on itself,” Greaves says.

It is possible that there is more here than meets the eyepiece. There

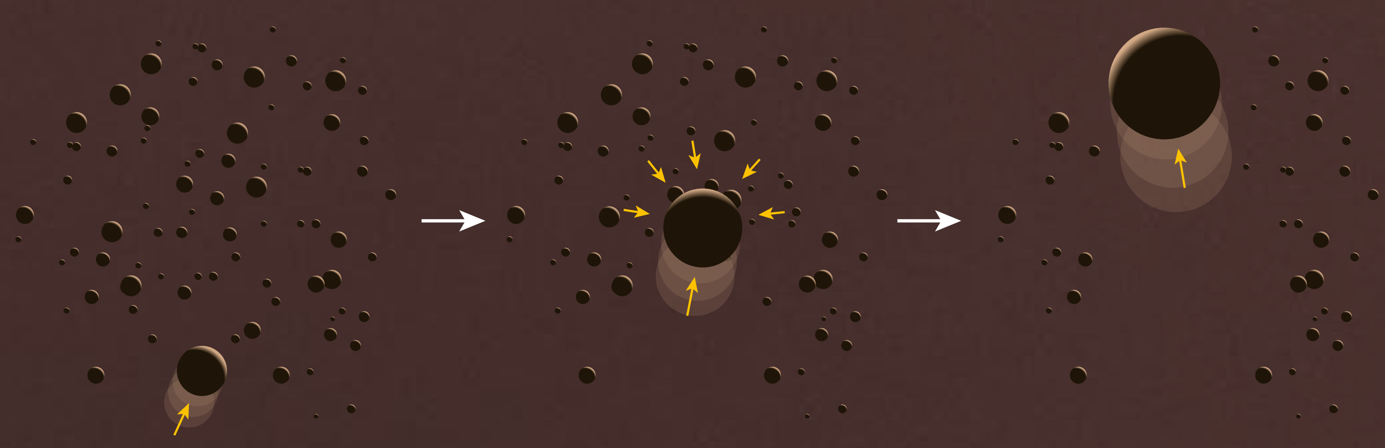
STREAMING INSTABILITY

Another scenario proposes instead a gravitational collapse, in which density variations cause solid lumps to collapse into asteroid-sized “planetesimals,” which then grow into protoplanets by other means.



PEBBLE ACCRETION

One way in which such planetesimals might grow is described in a third theory, which proposes that larger pieces of debris draw in smaller “pebbles” as they move through the disk. Thanks to both gravitational hydrodynamic interactions, these small pieces adhere like snow to a rolling snowball.



could, for example, be material in the disk that is difficult for telescopes to catch. Or, as Manara and his colleague Alessandro Morbidelli, a dynamicist at the Côte d'Azur Observatory in Nice, France, suggest, astronomers might be seeing only a snapshot; stars might be accreting new material from outside the protoplanetary disk, from the molecular clouds that forged them.

This theft could be hard to spot. But in research published in 2017, astrophysicist Hsi-Wei Yen at the ESO and his colleagues described two gas streams that seem to be connected to HL Tauri's disk—although they couldn't tell whether the gas was flowing toward or away from the star. If it were heading toward the star, Morbidelli says, the inflowing gas would have wide impacts, because it would also affect factors such as the disk's temperature, density and magnetism. Finding evidence of such flows suggests that stars and planets are not isolated from the larger cosmos as they form and grow. "The disk is not in a box," he says, "and this is also a revolution in our thinking about disks."

PLANETARY MENAGERIE

As if theorists did not already have enough to grapple with, observations of planetary nurseries continue to pile up. The latest findings lend weight to the idea that planets are forming early in the lives of their stars, and at distances from them that vary widely.

And it's not just ALMA that's been supplying images. Astronomers have also turned to the SPHERE instrument mounted on the ESO's Very Large Telescope. This, too, is in the Atacama Desert, about a six-hour drive south of ALMA. SPHERE has a system that can cancel out the blurring effects of the atmosphere and a filter that blocks starlight. In April, astronomers announced that they had used it to capture a diverse array of disks around eight young sunlike stars. Some resembled wide platters, some had distinct racetrack-like ovals, and one resembled a galaxy with jets streaming from its center. Such diversity suggests that planet-forming is a complex process yielding many possible outcomes.

Just two months later, news came that ALMA had been used to snap what might be the youngest exoplanets ever seen, orbiting a 4-million-year-old star about 100 parsecs (330 light years) from Earth. ALMA, which is at its most sensitive when viewing small, cool objects, cannot see starlight reflecting off the planets directly. But the swirl of carbon monoxide gas in the disk of the star suggests that three planets—each roughly the mass of Jupiter—are in orbit, forcing gas to flow around them, as rocks control the flow of a stream.

Not to be outdone, astronomers who had turned SPHERE towards another young star, called PDS 70, managed to nab a direct image of a gas giant. The planet orbits its star about four times farther than Jupiter does from the sun, and is still gobbling up material from its natal disk of dust and gas. The observation confirms the prediction that gas planets such as Jupiter form at vast separations from their stars.

Another instrument, the Gemini Planet Imager (GPI), which is mounted on the Gemini South Telescope in Chile's Andean foothills, has also been capturing disks with planets embedded in them, including a large gas giant that seems to support the core-accretion scenario of planet formation. As more observations roll in, lingering doubts about whether these young nurseries are really cradling planets—and not, say, displaying instabilities in their disks—are being put to rest. "Almost all of the features that we see can be explained most easily by planets," says Follette, who works on the GPI.

But the latest findings are also showing astronomers that the universe is much more complex and richly detailed than even our most advanced theories can predict. Several astronomers are realizing that the theoretical work they were doing a decade ago is no longer valid, but they are still not sure how to fix it.

"There's always that aspect; I'm sad that the stuff I did in the past isn't right any more. But the truth is, it was never right," says Sean Raymond, an astronomer at the Bordeaux Astrophysics Laboratory in France. "It was hopefully a step forward."

Observations might be of limited use in resolving the picture. ALMA and other radio observatories can see the dust and gas surrounding young stars, and optical instruments such as SPHERE and the GPI can see the disks and planets embedded in them, lit up with reflected starlight. But the range between tiny debris and 1,000-kilometer worlds will remain invisible.

Still, current and future telescopes could help to fill in some gaps. Astronomers could reach beyond ALMA's millimeter-scale vision to the centimeter range, Greaves says, with higher-resolution radio observations from telescopes such as the United Kingdom's Merlin array—as well as from the forthcoming Square Kilometer Array, due to be hosted in South Africa and western Australia. Such observations could partly bridge the span between dust and protoplanet. Greaves eagerly anticipates the possibility of finding centimeter-scale material swirling around what could be future rocky planets. "Seeing a spot in a disk that indicated an Earth forming at an Earth-like distance from its star—that's the new holy grail, at least for me."

With the observation of protoplanetary disks still in its infancy, the full story of planet-making will probably be more complicated than anyone expects, and ideas could well be overturned and then overturned again. "Case in point, it looks like the solar system isn't even the most common-looking system out there. We're a little weird," says Clement. "It turns out there is a lot of complexity out there."

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OBSERVATIONS

Photons, Quasars and the Possibility of Free Will

Flickers of light from the edge of the cosmos help physicists advance the idea that the future is not predetermined

Artist's rendering of the distant quasar ULAS J1120+0641.

Life is full of choices. Do we have a cookie or go to the gym? Do we binge watch our favorite show on Netflix or go to bed at a reasonable time? Our choices have consequences, and we make them of our own free will. Or do we?

The nature of free will has long inspired philosophical debates, but it also raises a central question about the fundamental nature of the universe. Is the cosmos governed by strict physical laws that determine its fate from the big bang until the end of time? Or do the laws of nature sometimes allow for things to happen at random? A century-old series of physics experiments still hasn't been able to settle the question, but a new experiment has tilted the odds toward the latter by performing a quantum experiment across billions of light-years.

The laws of classical physics are deterministic. Newton's mathematical cosmos is a clockwork universe, where each cause has a unique effect and we are governed not by our choices but by the rigid laws of nature. Quantum physics, on the other hand, has a property of fuzzy randomness, which some scientists feel could open the door to free will. Since quantum physics lies at the heart of reality, it would seem that randomness wins the day.

But some scientists have argued that quantum randomness isn't truly random. If I roll a die the outcome seems random, but it isn't really. All of its bumps and turns are caused by the forces of gravity and the table in a complex dance, but that dance is deterministic. The moment the die leaves my hand, its fate is sealed, even though I don't know the outcome until it happens. Perhaps quantum objects behave in the same way. They seem to act in random ways, but they are really governed by some deterministic hidden variables.

It is a question that has fascinated me since graduate school. My dissertation focused on aspects of quantum gravity, a subject that we still don't fully understand. One of the reasons for this is that we don't know how Einstein's deterministic theory of gravity can fit together with the randomness of quantum mechanics. The question fascinated Einstein as well, and being much smarter than me, he came up with an experiment that could test the idea. Together with Boris Podolsky and Nathan Rosen he presented a thought experiment now known as the Einstein-Podolsky-Rosen experiment, or EPR experiment for short.

To understand the experiment, suppose we have a mischievous mutual friend named Jane. Whenever Jane wears out a pair of running shoes, she loves to prank us by sending one shoe to each of us. So, whenever you get a shoe in the mail from Jane, you know I've gotten one too. One of us gets the right shoe, the other the left. But until either of us open our respective box, neither of us know which shoe we have. Once the box arrives at your door, you open it up, and find you have the left shoe. At that moment, you know I must have the right shoe.

This is the basic idea of the EPR experiment. It's nothing more than a silly prank in our everyday world,

Quantum physics, on the other hand, has a property of fuzzy randomness, which some scientists feel could open the door to free will.

but for quantum objects it gets really strange. You may have heard of Schrödinger's cat, where a quantum cat is neither alive nor dead until observed in a definite state. Like classical cats, quantum cats like quantum boxes. In the quantum realm things can be in an indefinite state until you observe them. It would be as if our boxes contained a pair of something (gloves, shoes, salt and pepper shakers, etc.) but it is impossible to know what specific something until one of us opens their box. Even stranger, how we measure quantum objects determines what the outcome can be. It would be as if opening the box on the side forces it to be a glove, while opening it from the top forces it to be a shoe. How I open my box affects your box miles away. In quantum theory, we say that our two boxes are entangled, so that observing the content of one box also tells us something about the other.

We can't do this experiment for gloves and shoes, but we can do it with light. Two entangled photons can be sent in opposite directions. I measure the orientation of one photon at random, you measure the other, and then we compare our results. There are lots of different orientations we would measure, so we can each choose the orientation we want. When this experiment is done in the lab, it actually works. And if our measurements are random, there is no way for the photons to know ahead of time which orientation will be measured. So, there can't be any hidden variable to determine the outcome. Whether we get the left or right shoe, or the left or right glove, the result is truly random.

This is the heart of why Einstein referred to entanglement as "spooky action at a distance." It's spooky because entangled objects have a quantum connection, even if they are light-years apart. So, a measurement on one object is a measurement on both through this spooky entanglement. But it's only spooky if the measurement we make is random. If it's not random, then no spooky connection is necessary to explain the EPR results.

This is known as the "freedom of choice" loophole. EPR experiments are done in a lab, and even though the choice of how to measure the photons seems random, if there's no free will then the observation we make was determined by earlier conditions. Since it takes time to set up the experiment in a lab, it's possible that there are small interactions that could let the quantum system know ahead of time what measurement will be done. Maybe the experiment, the scientists and the lab are all entangled in such a way that the outcome isn't truly random, so the quantum objects can game the outcome.

To get around the loophole, you have to deal with the speed of light. It's often said that nothing can travel faster than the speed of light, but it's really information that can't travel faster than light. We can send each other telegrams or text messages, but never faster than the time it takes for light to travel between us. In a small lab, light has plenty of time to travel back and forth across the room while the experiment is being set up, so perhaps small bits of information bias the “random” aspect of experiment before it’s even done. That doesn’t seem very likely, but a new experiment has overcome this problem. Rather than using a random number generator in the lab to decide which photon measurement to make, the experimenters used quasars.

Quasars are brilliant beacons of light powered by supermassive black holes in the centers of distant galaxies. The team used random fluctuations in the light from quasars to determine how the photons were measured. Since the light from a quasar has to travel for billions of years to reach us, the fluctuations in brightness happened billions of years before the experiment was done—billions of years before humans even walked the Earth. So, there is absolutely no way for it to be entangled with the experiment.

The result was just what quantum theory predicts. Thus, it looks like there really are no deterministic hidden variables, and randomness is still possible throughout the cosmos.

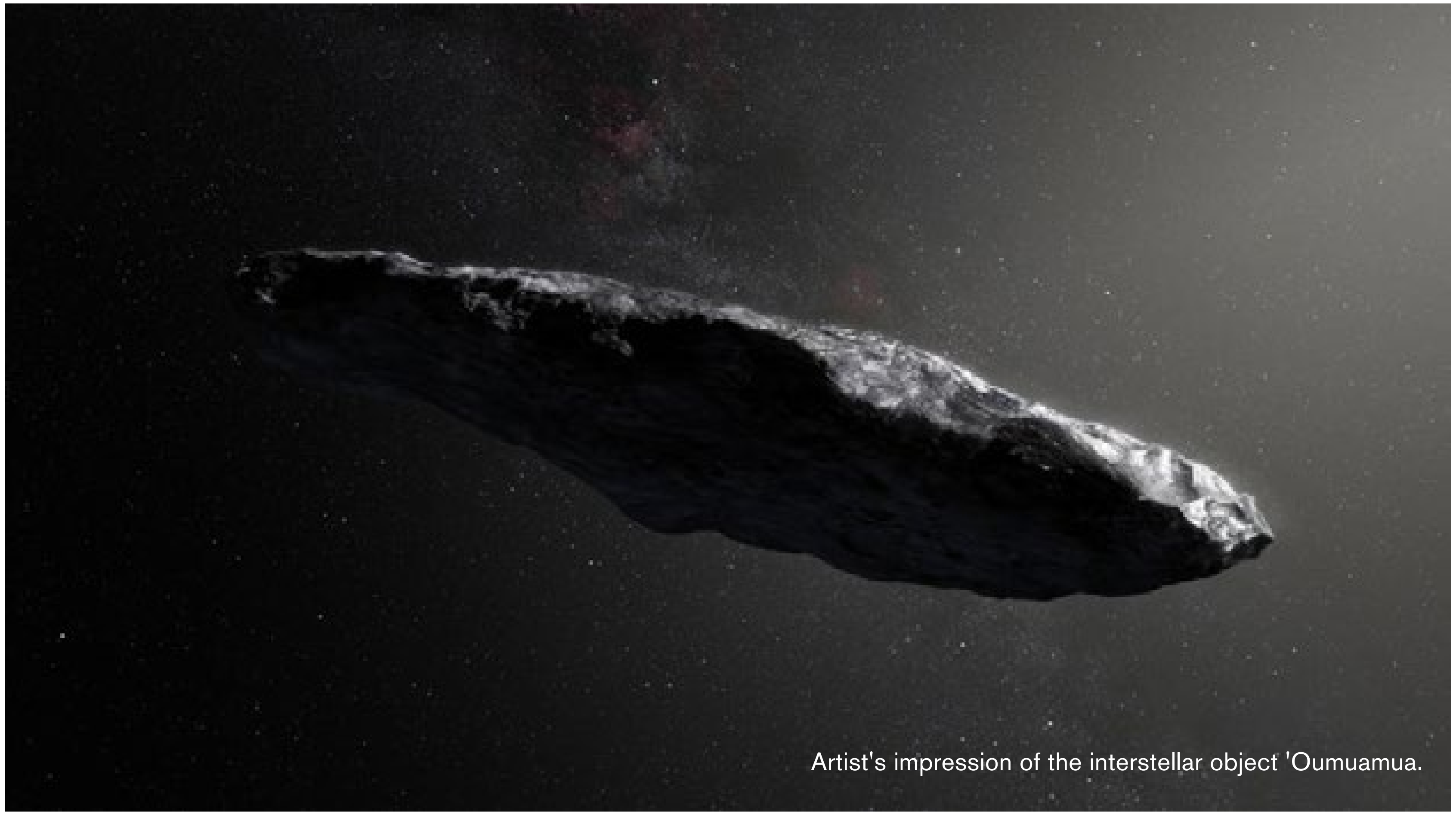
Of course, randomness isn’t the only thing necessary for free will. But it does mean that your fate is not necessarily sealed. So, when you resist that second cookie, or turn off the TV in the evening, you can take pride in the fact that maybe, just maybe, the choice was yours after all.

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

OBSERVATIONS

How to Approach the Problem of 'Oumuamua

The first interstellar object ever found provides an excellent test of the scientific process



Artist's impression of the interstellar object 'Oumuamua.

On October 19, 2017, the first interstellar object detected in the solar system, 'Oumuamua, was discovered by the Pan-STARRS survey. The six anomalies exhibited by this weird object since its discovery imply that it is nothing like the garden variety of asteroids or comets born in the solar system. What is it then? 'Oumuamua's deviation from a Keplerian orbit around the sun, combined with the lack of evidence for cometary outgassing, promoted the option that it might be a lightsail of artificial origin.

As a result, numerous reporters asked me recently for the "gut feeling likelihood" that I assign to the possibility that 'Oumuamua is artificial. I declined to give them a quantitative answer. My past experience taught me not to rely on gut feelings in situations like this, because gut feeling is guided by prejudice (labeled by Bayesian statisticians as the "prior probability"). And prejudice is shaped by experience, so we bring the risk of missing unexpected discoveries if we always expect the future to resemble the past.

Some social media aficionados declared with great confidence that 'Oumuamua is not artificial in origin. But they did not provide evidence to support their claim. They argued along the lines that "there are things we do not understand, which are nevertheless thought to originate from natural causes."

But this is no excuse for leaving the artificial-origin option off the table for 'Oumuamua. The notion that an alien civilization might exist rests on the facts that our civilization exists and that the physical conditions on the surfaces of many other planets resemble those on Earth. The possibility of a "message in a bottle" from another civilization should therefore not be dismissed ab initio. After all, there are mainstream concepts that are far more imaginative than this possibility, but similarly unproven.

For example, what could be stranger than postulating the existence of extra dimensions in order to unify quantum mechanics and gravity? Or postulating a new form of matter made of as-yet-undiscovered particles to explain the motion of stars in galaxies? Yet, the concepts of extra dimensions and dark matter serve as mainstream dogmas in physics and astronomy today.

Why do scientists contemplate the existence of a new form of matter instead of arguing that there are things we do not understand about ordinary matter? Because ordinary matter shows anomalous motions, and conventional interpretations of these anomalies are not compelling. In the same vein, ‘Oumuamua showed an anomalous orbit, and conventional cometary outgassing was tightly constrained by the Spitzer Space Telescope, which did not detect dust or carbon-based molecules in the vicinity of the object and found it to be at least 10 times more shiny than a typical comet.

In addition, the spin period of ‘Oumuamua did not change as we would expect from cometary outgassing. If the advocates for a natural origin of ‘Oumuamua have a good explanation for its orbital anomaly and lack of detectable outgassing, they should present this explanation in a scientific paper so that it would be tested with future analysis of existing data or future data on similar objects. This would be equivalent to suggesting theories of dark matter made of conventional material, or modified gravity, as alternatives to the notion of a new form of invisible matter.

Galileo Galilei taught us through experimentation that despite our gut feeling, heavy objects do not fall faster than light objects. Similarly, experiments have taught us that “spooky action at a distance” is a feature of quantum mechanics, despite Albert Einstein’s gut feeling that such a thing was impossible. The lesson from these historic examples is that in questions of science, we should base our inferences on evidence and not prejudice. Before the truth becomes evident, there is a long period of uncertainty with some “gut feelings” being misguided.

How can we gather more data on the population of ‘Oumuamua-like objects, so as to shorten the period of uncertainty about their origin? The simplest approach would be to seek new interstellar objects in surveying the sky. The Large Synoptic Survey Telescope (LSST) will offer far better sensitivity than Pan-STARRS and should find many ‘Oumuamua-like objects once it starts operating in a few years. If LSST does not find any new interstellar objects, we will recognize a seventh anomaly about ‘Oumuamua, namely that it was special. In such a case, we would have to chase it down in order to learn more about its mysterious origin.

Out of the entire population of interstellar objects, there should be a small subset that passed close to Jupiter, lost orbital energy and became trapped in the solar system. For these objects, the sun-Jupiter system acts as a fishing net.

In a new paper with Harvard undergraduate Amir Siraj, we found that the trapped ‘Oumuamua-like objects could be distinguished from asteroids or comets that were born in the solar system based on their unusual orbits, which would sometimes be highly inclined or counter-rotating relative to the planets. In addition to predicting tens of expected discoveries by LSST, our paper identified four specific candidates for trapped interstellar objects that might already have been discovered by past surveys.

Fly-by photography or landing on trapped interstellar objects would educate us about their shape, composition and origins, saving the need to send interstellar probes to their distant birthplaces. We might also discover traces of primitive life-forms on them from another planetary system, confirming the possibility of interstellar panspermia. But ultimately, the search for “a message in a bottle” provides a unique opportunity for finding out that we are not alone, even if only one out of many interstellar objects originates from a technological civilization.

Since ‘Oumuamua appears to be weird, its birthplace must be very different from what we currently imagine, irrespective of whether it is natural or artificial. And the most important point to keep in mind is that this object is what it is, independent of what the popular opinion is on Twitter.

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WILLEM DOUVEN *GETTY IMAGES*

OBSERVATIONS

Do We Actually Experience the Flow of Time?

Subjective experience must inform physics and philosophy, but it should be assessed carefully

Time is a contentious topic in physics. Some physicists, such as Julian Barbour, argue that it doesn't even exist. Others, such as Carlo Rovelli, hold that it arises as a secondary effect of deeper quantum processes. Yet others, such as Lee Smolin, maintain that time is the sole fundamental dimension of nature. And because the laws of physics are time-symmetrical, much debate has gone into figuring out why we seem unable to travel back in time.

All this theorizing is motivated by—and attempts to make sense of—our subjective experience of the forward flow of time. Indeed, our reliance on what we *think* we experience as the flow of time goes so deep that some philosophers take it for a self-evident axiom. For instance, writing for this magazine, Susan Schneider claimed that the flow of time is inherent to experience—so much so that, according to her, "timeless experience is an oxymoron."

But do we actually experience the flow of time? We certainly experience something that looks like it. But if we introspect carefully into this experience, is what we find accurately describable as "flow"?

There can only be experiential flow if there is experience in the past, present and future. But where is the past? Is it anywhere out there? Can you point at it? Clearly not. What makes you conceive of the idea of the past is the fact that you have memories. But these memories can only be referenced insofar as they are experienced *now*, as memories. There has never been a single point in your entire life in which the past has been anything other than memories experienced in the present.

The same applies to the future: where is it? Can you point at it and say "there is the future"? Clearly not. Our conception of the future arises from expectations or imaginings experienced now, always now, as expectations or imaginings. There has never been a single point in your life in which the future has been anything other than expectations or imaginings experienced in the present.

But if the past and the future are not actually experienced in the, well, past and future, how can there be an experiential flow of time? Where is experiential time flowing from and into?

Let's make an analogy with space. Suppose that you suddenly find yourself sitting on the side of a long, straight desert road. Looking ahead, you see mountains in the distance. Looking behind, you see a dry valley. The mountains and the valley provide references that allow you to locate yourself in space. But the mountains, the valley, your sitting on the roadside, all exist simultaneously in the present snapshot of your conscious life.

An entirely analogous situation occurs in time: right now, you find yourself reading this essay. As you read it, you can remember having done something else—say, having brushed your teeth—earlier today. You can also imagine that you will do something else later—say, lie down in bed. Brushing your teeth and lying down in bed are respectively behind and ahead of you on the road of time—your "timescape"—just as the valley and the mountains were on the road of space. They provide references that allow you to locate yourself in time. But again, the experiences of remembering the past and imagining the future, as well as that of reading this essay right now, all exist simultaneously in the present snapshot of your conscious life.

The problem is that we then construe from this that there is an experiential flow of time. Such a conclusion is as unjustifiable as to construe, purely from seeing the mountains ahead and the valley behind while you sit by the roadside, that you are moving on the road. You aren't; you are simply taking account of your relative position on it. You have no more experiential reason to believe that time flows than that space flows while you sit quietly by the roadside.

You may claim that, whereas the desert road scenario is static, lacking action, you actually did brush your teeth earlier. So time definitely flowed from then to now; or did it? All you have supporting belief that it did is your memory of having brushed your teeth, which you experience now. All you ever have is the present experiential snapshot. Even the notion of a previous or subsequent snapshot is—insofar as you can know from experience—merely a memory or expectation *within the present snapshot*. The flow from snapshot to snapshot is a story you tell yourself, irresistibly compelling as it may be. Neuroscience itself suggests that this flow is indeed a cognitive construct.

A thought experiment may help: suppose that you could return to your past—say, back to the moment when you were brushing your teeth this morning. In the corresponding experiential snapshot, the present would lie between, say, the memory of your having stood up from bed and the expectation of your dressing up for work. But once you landed on that snapshot, you would have no experience of any temporal discontinuity: you would look behind in memory and see yourself standing up from bed; you would look ahead in imagination and see yourself dressing up for work. The tape of history would have been rewound and you would have no memory of having time-traveled; otherwise you wouldn't have actually time-traveled. Everything would feel perfectly normal—*just as it feels right now*. So who is to say that you haven't time-traveled a moment ago? How do you know that time always flows forward?

You see, whether time flows forward, or doesn't flow at all, or moves back and forth, our resulting subjective experience would be identical in all cases: we would always find ourselves in an experiential snapshot extending smoothly backwards in memory and forwards in expectation, just like the desert road. We would always tell ourselves the same story about what's going on. A mere cognitive narrative—based purely on contents of the experiential snapshot in question—would suffice to convince us of the forward flow of time *even when such is not the case*.

The ostensible experience of temporal flow is thus an illusion. All we ever actually experience is the present snapshot, which entails a timescape of memories and imaginings analogous to the landscape of valley and mountains. Everything else is a story. The implications of this realization for physics and philosophy are profound. Indeed, the relationship between time, experience and the nature of reality is liable to be very different from what we currently assume, as I discuss in my upcoming book, *The Idea of the World.* To advance our understanding of reality we must thus revise cherished assumptions about our experience of time.

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
February 2019

Day	Event
1	Morning sky: moon between Venus and Saturn
2	Morning sky: moon near Saturn
	Moon reaches southernmost declination (–22.4°)
4	Moon: new moon
5	Moon at apogee (406,555 km), apparent diameter 29’ 24”
12	Moon: first quarter
13	Evening sky: moon in the open cluster Hyades, near Aldebaran
	Mars 1.1° north of Uranus
16	Moon reaches northernmost declination (+20.9°)
18	Morning sky: Venus 1.1° north of Saturn
19	Moon at perigee (356,761 km), apparent diameter 33’ 28”
	Moon: full moon
26	Moon: last quarter
27	Mercury: greatest elongation east (18°)
	Morning sky: moon 3° northwest of Jupiter
28	Morning sky: moon between Jupiter and Saturn

February/March 2019: Visibility of planets

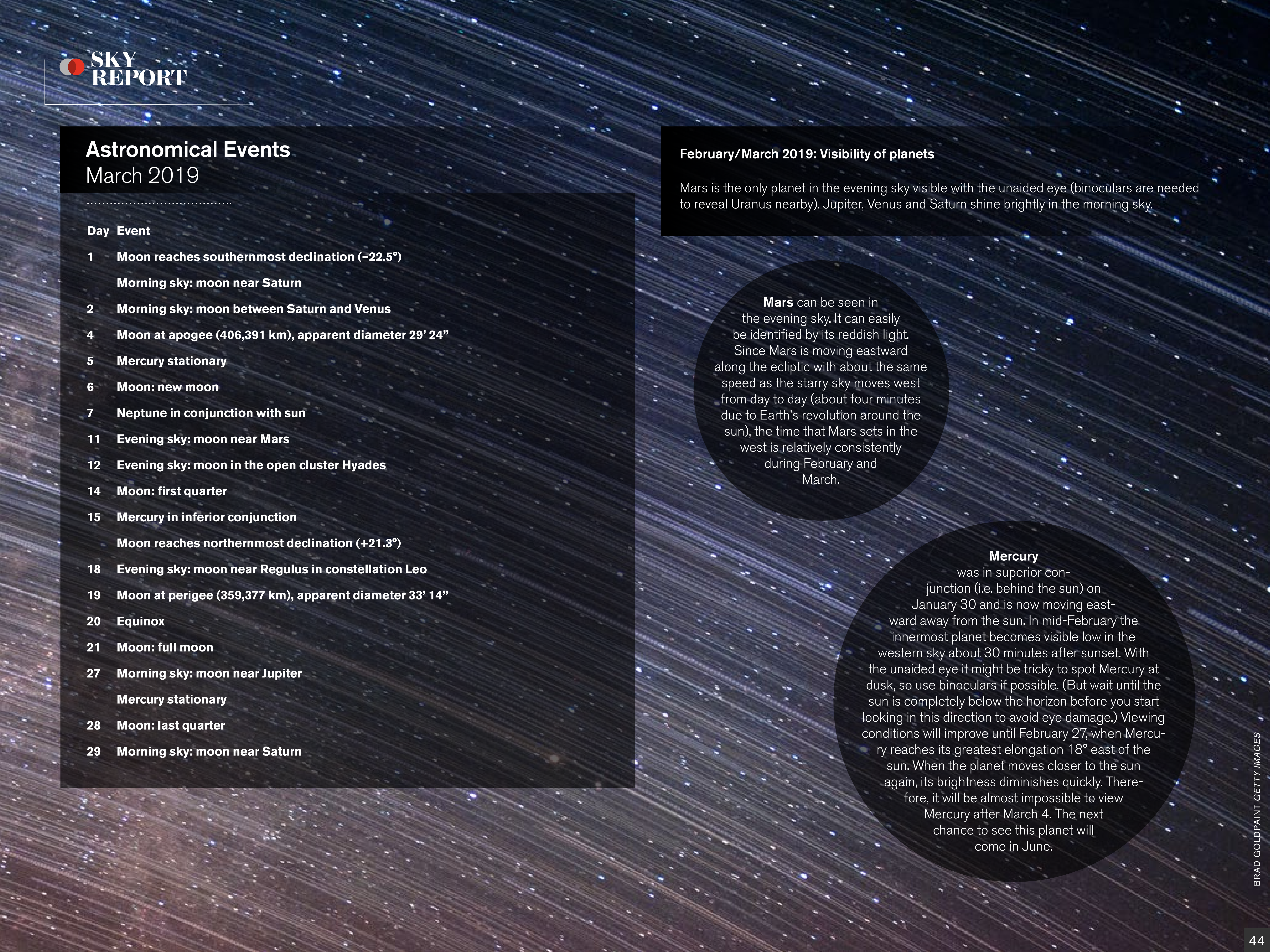
Mars is the only planet in the evening sky visible with the unaided eye (binoculars are needed to reveal Uranus nearby). Jupiter, Venus and Saturn shine brightly in the morning sky.

Venus shines as a brilliant “star” in the morning sky in the southeast. Throughout February, Venus moves away from Jupiter and toward Saturn some 25° farther to the east. On the morning of February 18, Venus and the ringed planet will form a close pair, separated by just 1° (about twice the diameter of the full moon). After passing by Saturn, Venus is further heading toward the sun, considerably shortening its visibility in the pre-dawn sky. Whereas Venus rises about three hours before the sun at the beginning of February, it rises only about two hours on March 1 and a little more than one hour by the end of March.

Saturn reemerges from behind the sun and joins the morning sky. At the beginning of February, the ringed planet rises about 90 minutes after Venus and 90 minutes before the sun. The visibility considerably improves throughout February and March.

Jupiter is in the constellation Ophiuchus in the morning sky. The giant planet rises ahead of Venus and Saturn. On the morning of February 27, Jupiter seems to hang just 3° below the waning crescent moon. The moon meets Jupiter again on March 27.

BRAD GOLDPAINT *GETTY IMAGES*



Astronomical Events
March 2019

Day	Event
1	Moon reaches southernmost declination (–22.5°)
	Morning sky: moon near Saturn
2	Morning sky: moon between Saturn and Venus
4	Moon at apogee (406,391 km), apparent diameter 29’ 24”
5	Mercury stationary
6	Moon: new moon
7	Neptune in conjunction with sun
11	Evening sky: moon near Mars
12	Evening sky: moon in the open cluster Hyades
14	Moon: first quarter
15	Mercury in inferior conjunction
	Moon reaches northernmost declination (+21.3°)
18	Evening sky: moon near Regulus in constellation Leo
19	Moon at perigee (359,377 km), apparent diameter 33’ 14”
20	Equinox
21	Moon: full moon
27	Morning sky: moon near Jupiter
	Mercury stationary
28	Moon: last quarter
29	Morning sky: moon near Saturn

February/March 2019: Visibility of planets

Mars is the only planet in the evening sky visible with the unaided eye (binoculars are needed to reveal Uranus nearby). Jupiter, Venus and Saturn shine brightly in the morning sky.

Mars can be seen in the evening sky. It can easily be identified by its reddish light. Since Mars is moving eastward along the ecliptic with about the same speed as the starry sky moves west from day to day (about four minutes due to Earth’s revolution around the sun), the time that Mars sets in the west is relatively consistently during February and March.

Mercury was in superior conjunction (i.e. behind the sun) on January 30 and is now moving eastward away from the sun. In mid-February the innermost planet becomes visible low in the western sky about 30 minutes after sunset. With the unaided eye it might be tricky to spot Mercury at dusk, so use binoculars if possible. (But wait until the sun is completely below the horizon before you start looking in this direction to avoid eye damage.) Viewing conditions will improve until February 27, when Mercury reaches its greatest elongation 18° east of the sun. When the planet moves closer to the sun again, its brightness diminishes quickly. Therefore, it will be almost impossible to view Mercury after March 4. The next chance to see this planet will come in June.

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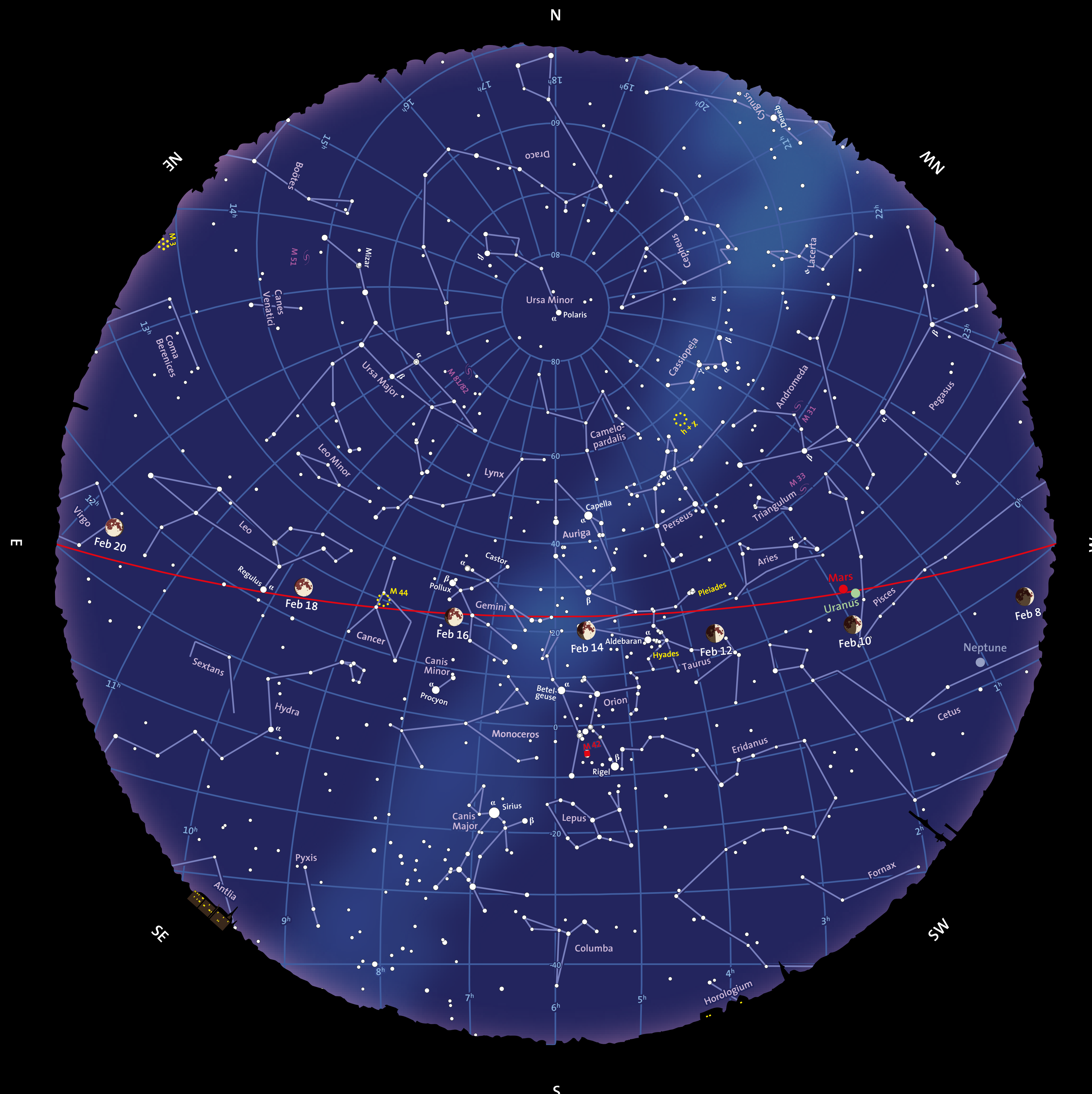
SKY REPORT

February

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



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

−1	0	1	2	3	4	5

Apparent magnitudes

- Open cluster
- Globular cluster
- Galaxy
- Nebula

ERNST VON VOIGT

SKY REPORT

March

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

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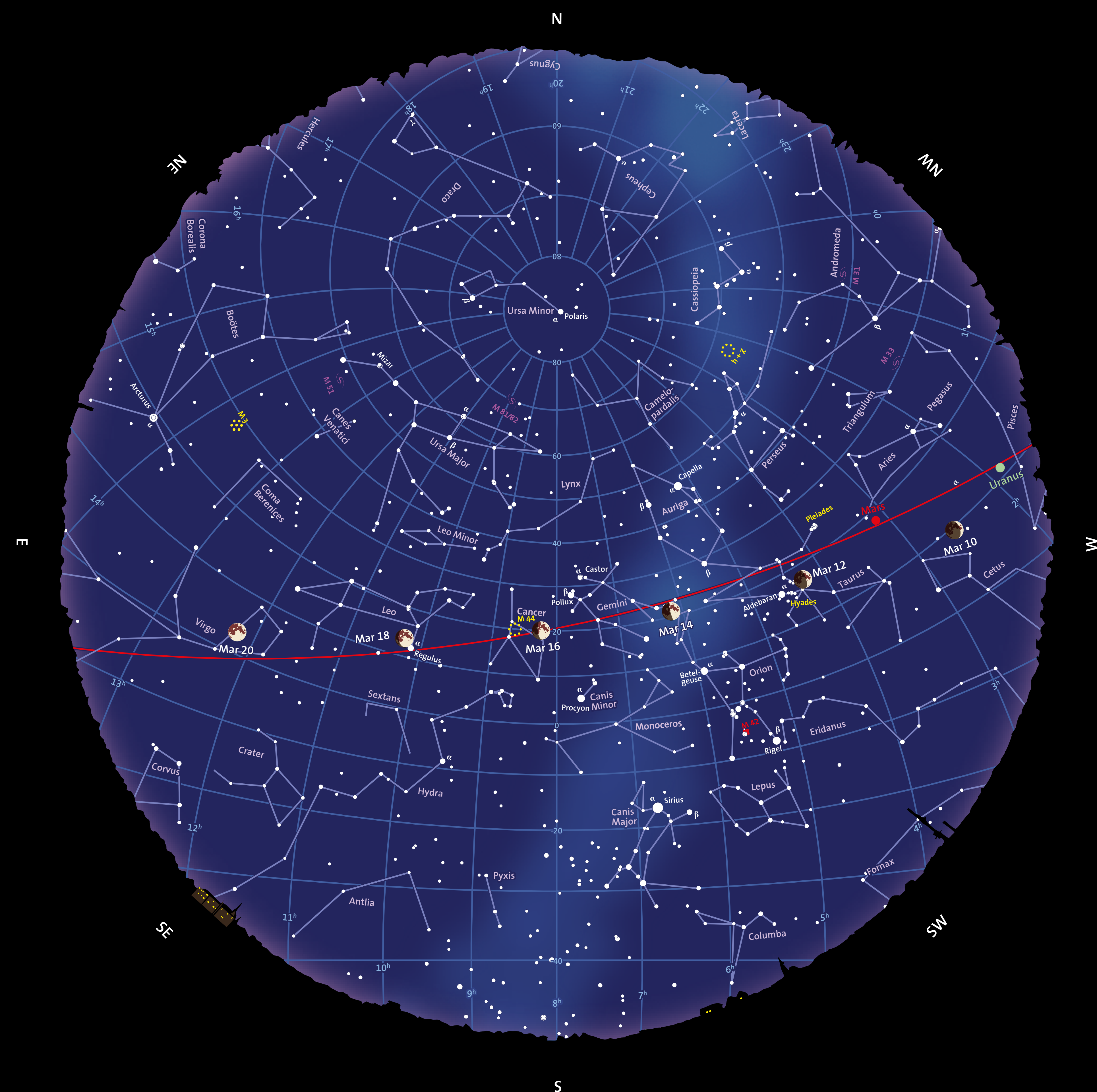
- Globular cluster
- Galaxy
- Nebula



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