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Space & Physics

Plus:

MISSING DARK MATTER

SPOTTING A QUANTUM GHOST

A NEW THEORY OF EXTRATERRESTRIAL LIFE

Mission of a Generation

SUCCESSFULLY LAUNCHED, THE JAMES WEBB SPACE TELESCOPE COULD REDEFINE ASTRONOMY

WITH COVERAGE FROM
nature

Liz Tormes

Cosmic-Level Anxiety

On this past Christmas Day, NASA scientists and engineers cheered and breathed a cautious sigh of relief for the first time in, likely, years. The James Webb Space Telescope launch had gone off successfully, after years of delay, budget overages and technical challenges. In the ensuing weeks, the anxiety has kept up a steady hum while the telescope performed crucial early mission tasks to get itself situated to start collecting data—namely, unfurling its sunshield and mirrors. Read Alexandra Witze's update outlining these accomplishments. The telescope's operators are far from relaxing, but each mission milestone marks the start of a new era of astronomy, as Richard Panek reports in this issue (see "The James Webb Space Telescope Has Launched: Now Comes the Hard Part").

NASA has another exciting mission underway: the Double Asteroid Redirection Test (DART). Designed as part of our planetary defense plan (see "NASA's DART Mission Could Help Cancel an Asteroid Apocalypse"), a test spacecraft launched at the end of last November and will smash into its target sometime in the fall of 2023. I anticipate many months of thrilling anxiety for NASA scientists. If all goes well, the payoffs will be cosmic.

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On the Cover

Successfully launched, the James Webb Space Telescope could redefine astronomy

ESA/D. Ducros

WHAT'S INSIDE

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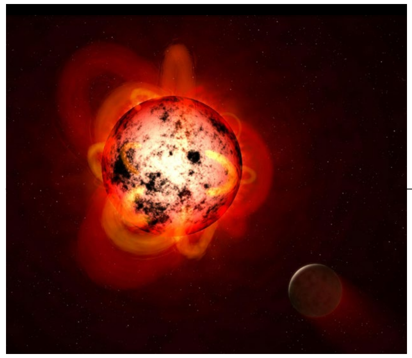
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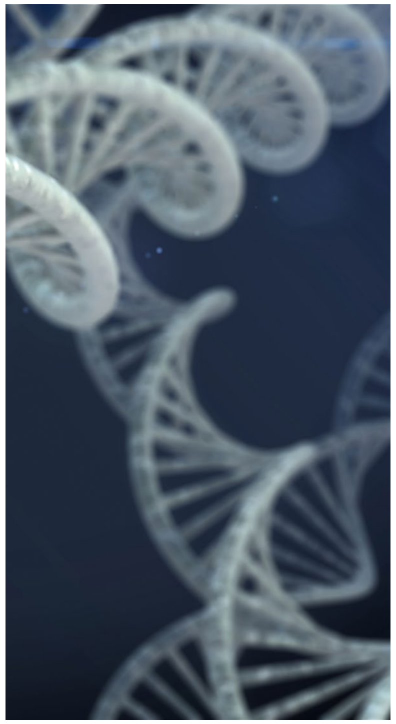
NEWS

4. NASA Spacecraft "Touches" the Sun for the First Time Ever
The Parker Solar Probe has passed through a boundary and into the sun's atmosphere, gathering data that will help scientists better understand stars

6. In a First, Physicists Glimpse a Quantum Ghost
After a decade of work, researchers have achieved the first-ever experimental reconstruction of a quantum wave function

8. Scientists Plan Private Mission to Hunt for Earths around Alpha Centauri
A privately funded telescope called Toliman will seek habitable worlds in our nearest neighboring star system, potentially sparking a new wave of exoplanetary exploration


elsar77/Getty Images

11. Life Is Complicated–Literally, Astrobiologists Say
A new theory suggests that searches for molecular complexity could uncover convincing evidence of extraterrestrial life—and do so soon

14. Heavy-Metal Exoplanet Found Orbiting Nearby Star
With a density close to that of pure iron, GJ 367b may be the remnant metal-rich core of an evaporated giant world

ESA/D. Ducros

FEATURES

16. The James Webb Space Telescope Has Launched: Now Comes the Hard Part
After years of delay, the most ambitious observatory ever built has at last left Earth. It now faces a high-stakes series of deployments in deep space

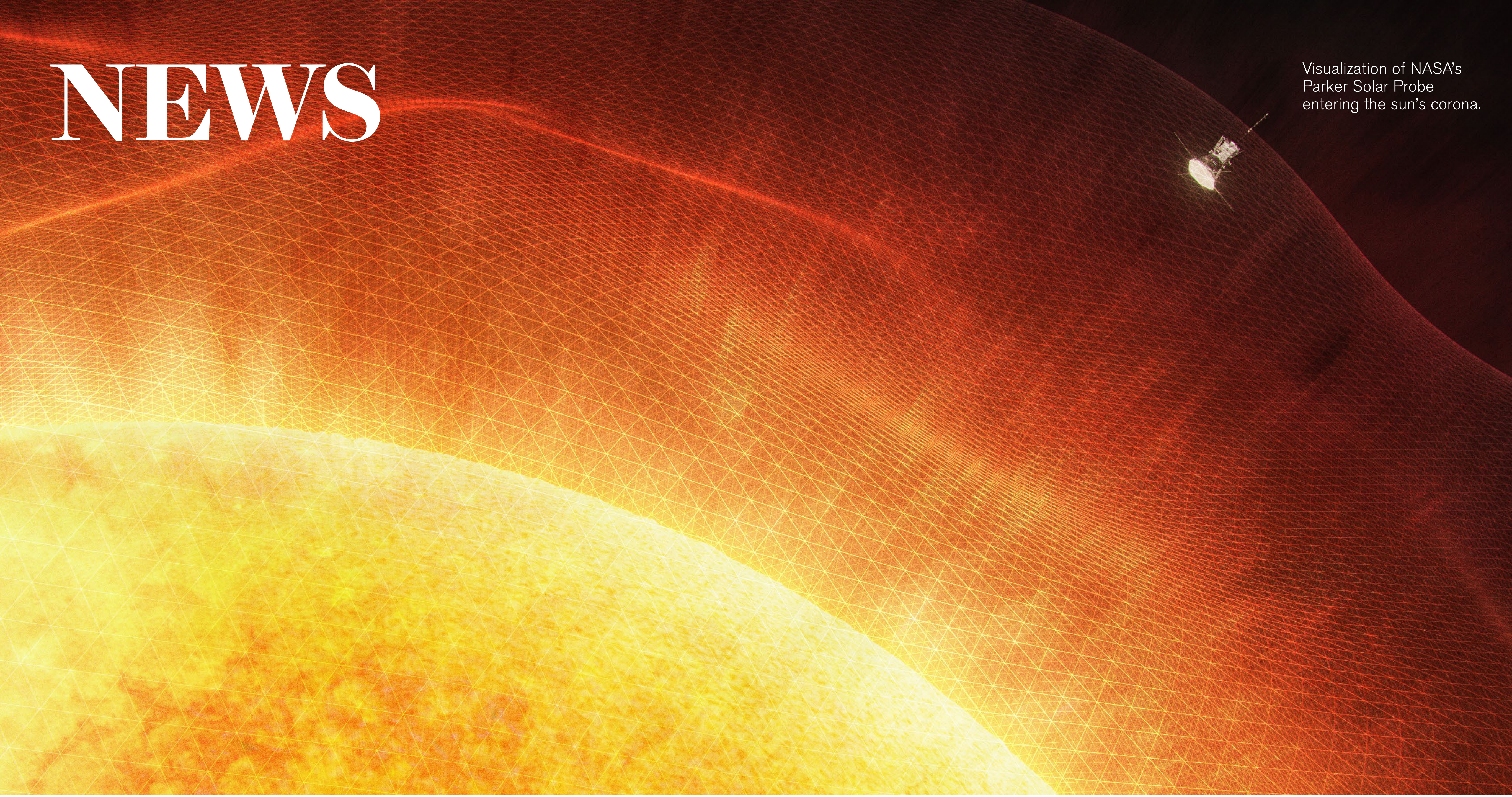
20. Dark Matter May Be Missing from This Newfound Galaxy, Astronomers Say
A growing number of galaxies seem to be bereft of the mysterious substance, posing fresh challenges for some of cosmology's most cherished theories

24. NASA's DART Mission Could Help Cancel an Asteroid Apocalypse
Our planet is vulnerable to thousands of "city killer" space rocks. If—when—one is found on a collision course with Earth, will we be ready to deflect it?

OPINION

30. When Did Life Start in the Universe?
Interstellar xenia, or the welcoming of cosmic strangers, could solve this mystery

NEWS



Visualization of NASA's Parker Solar Probe entering the sun's corona.

NASA's Goddard Space Flight Center/Joy Ng

NASA Spacecraft "Touches" the Sun for the First Time Ever

The Parker Solar Probe has passed through a boundary and into the sun's atmosphere, gathering data that will help scientists better understand stars

A NASA spacecraft has entered a previously unexplored region of the solar system—the sun's outer atmosphere, or corona. The long-awaited milestone, which happened last April but was announced on December 14, is a major accomplishment for the Parker Solar Probe, a craft that is flying closer to the sun than any mission in history.

"We have finally arrived," said Nicola Fox, director of NASA's heliophysics division, located at the agency's headquarters in Washington, D.C. "Humanity has touched the sun."

She and other team members spoke during a press conference last December at the American Geophysical Union meeting in New Orleans. A paper describing the findings appears in *Physical Review Letters.*

In many ways, the Parker Solar Probe is a counterpoint to NASA's twin Voyager spacecraft. In 2012 Voyager 1 traveled so far from the sun that it became the first mission to leave behind the region of space dominated by the solar wind—the energetic flood of particles coming from the sun. In contrast, the Parker probe is flying ever closer toward the heart of the solar system, head-on into the solar wind and into our star's atmosphere. With this new front-row seat, scientists can explore some of the biggest unanswered questions about the sun, such as how it generates the solar wind and how its corona gets heated to temperatures more extreme than those on the sun's surface.

"This is a huge milestone," says Craig DeForest, a solar physicist at the Southwest Research Institute in Boulder, Colo., who is not involved with the mission. Flying into the solar corona represents "one of the last great unknowns," he says.

INTO THE UNKNOWN

The Parker probe crossed into the sun's atmosphere at 9:33 A.M. Universal Time on April 28, 2021. It took several months for mission scientists to download and analyze the data it collected and to be sure that the spacecraft had indeed crossed the much anticipated boundary, known as the Alfvén surface.

This surface marks the interface between the sun's atmosphere and an outer region of space dominated by the solar wind. Swedish physicist Hannes Alfvén proposed the underlying theory behind the boundary in a paper in *Nature* in 1942, and scientists have been looking for it ever since.

But it took the $1.5-billion Parker Solar Probe to finally get there. Since its launch in 2018, it has been orbiting the sun and looping ever closer to the solar surface on each pass. A carbon-composite heat shield protects its instruments from temperatures that will eventually soar to 1,370 degrees Celsius.

The spacecraft crossed the Alfvén boundary when it was around 14 million kilometers, or just under 20 solar radii, from the sun's surface. That's about where team members had expected to find the interface, says Nour Raouafi, the mission's project scientist at the Johns Hopkins University Applied Physics Laboratory.

Some researchers had speculated that the boundary would be rather fuzzy, but it was instead somewhat sharp and wrinkly. The spacecraft passed into the corona for nearly five hours and then back out again and might have crossed into it briefly twice more. Inside the corona, the solar wind speed and plasma densities dropped, suggesting the boundary had indeed been crossed. "We are learning new things that we did not have access to before," Raouafi says.

STREAMERS AND SWITCHBACKS

As it crossed the Alfvén surface, the Parker probe flew through a "pseudostream" of electrically charged material, inside which conditions were quieter than the roiling environment outside. While inside the corona, the spacecraft also studied unusual kinks in the magnetic field of the solar wind, known as switchbacks. Scientists knew about switchbacks previously, but the Parker Solar Probe data have allowed them to trace where they come from, all the way down to the solar surface.

Knowing how such features form on the sun, and how they influence the solar wind and other eruptions of charged particles, will help people on Earth better prepare for disruptive space weather, such as when solar storms knock out satellite communications. The discoveries will also help researchers better understand the forces that power stars other than the sun, said Kelly Korreck, a solar physicist at NASA's headquarters.

The Parker Solar Probe ultimately aims to make 24 close passes by the sun. It crossed the Alfvén surface on the eighth of those flybys and might have done so again during its ninth pass in November 2021—a maneuver for which the data have not yet been fully downloaded and analyzed. The mission's closest approach is scheduled for 2025 at a distance of just 6.2 million kilometers from the solar surface, well within the orbit of Mercury. Each visit will continue to reveal new information about processes within the corona, said Justin Kasper, a solar physicist and deputy chief technology officer at BWX Technologies in Washington, D.C., who works on the Parker probe.

"Being this close to the sun is allowing us to make really interesting and new connections we wouldn't be able to do from afar," he said.

—Alexandra Witze

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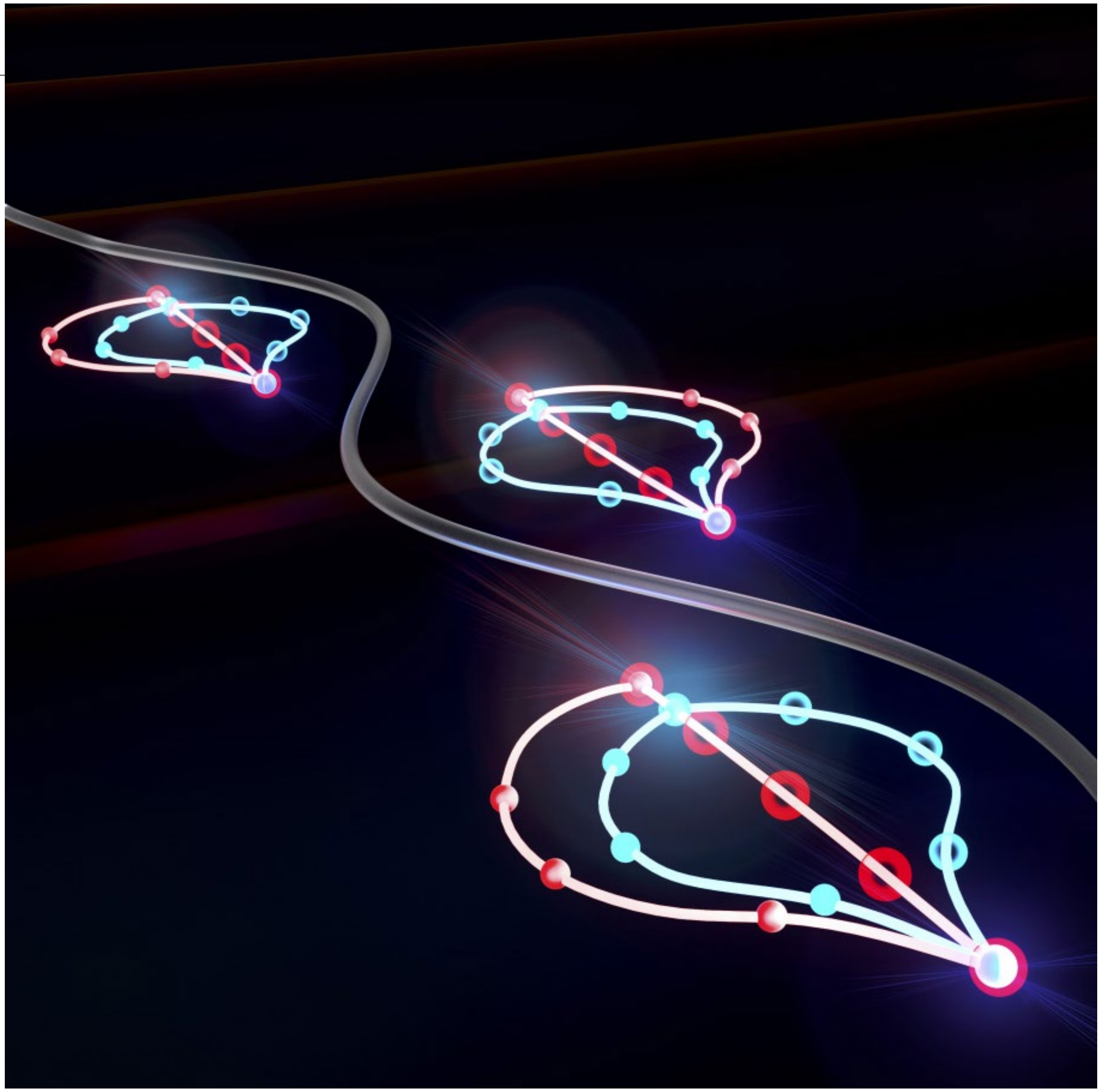
In a First, Physicists Glimpse a Quantum Ghost

After a decade of work, researchers have achieved the first ever experimental reconstruction of a quantum wave function

The wave function—an abstract concept used to predict the behavior of quantum particles—is the bedrock on which physicists have built their understanding of quantum mechanics. But this bedrock itself is not something physicists have a perfect grasp of, literally or philosophically. A wave function is not something one can hold in one's hand or put under a microscope. And confusingly, some of its properties simply seem not to be real. In fact, mathematicians would openly label them as imaginary: so-called imaginary numbers—which arise from seemingly nonsensical feats such as taking the square roots of negative integers—are an important ingredient of a wave function's well-proved power to forecast the results of real-world experiments. In short, if a wave function can be said to "exist" at all, it does so at the hazy crossroads between metaphysical mathematics and physical reality.

Now researchers at the University of California, Santa Barbara, and their colleagues have made big strides in bridging these two realms: for the first time, they reconstructed a wave function from a measurement of how a semiconductor material responds to an ultrafast pulse of light. Appearing in *Nature* last November, the team's work may help take electronics engineering and quantum materials design into a new era of fine-tuned understanding and precisely controlled innovation.

For real-world applications, such as modern electronics, the somewhat mysterious wave function is physicists' best source of information about what actually happens inside of some new gadget. To predict how fast an electron moves inside a material or how much energy it can carry, they must start their calculations with the so-called Bloch wave function—named for physicist Felix Bloch, who devised it in 1929. This is especially important for engineering quantum devices, says Joe Costello, a physics student at U.C.S.B. and co-lead author of the recent study. "If you're thinking about building any sort of device that takes advantage of quantum mechanics, you're going to need to know its [wave function's] parameters really well," he emphasizes.



Artist's impression of electrons within a semiconductor being accelerated and energized by laser pulses. At the end of the process, the electrons release a burst of light carrying information about their quantum wave function.

Brian Long

This includes the wave function's so-called phase, a fully imaginary parameter that is nonetheless often crucial for designing quantum computers. "What has been characterized for a long time is the energies [of the electrons]. That's the basis for all electronics," says Mackillo Kira, a physicist at the

University of Michigan, who read an earlier draft of the study but was not directly involved in the work. “But now, with quantum information technology, the next level is to go beyond that and eventually get these [wave function] phases.”

To make it to that next level, the team members used two lasers and the semiconductor material gallium arsenide. Their experiment consisted of three steps: First, they hit the electrons inside the material with a pulse of near-infrared laser light. This gave those particles extra energy so they would start to quickly race through the semiconductor. When each negatively charged electron started its race, a so-called hole, something like its shadow particle—identical to the electron but positively charged—moved with it. Next, the researchers used another laser pulse to tear the hole and the electron apart, then quickly allowed them to reunite—a sort of quantum version of Peter Pan losing his shadow and having it reattached. When the hole and the electron recombined, the extra energy each accumulated while running solo was released as a burst of light.

Ten years ago a team of physicists led by Mark Sherwin of U.C.S.B. noticed something curious about these bursts: their properties were inexplicably sensitive to the properties of the laser pulses that started the particle run in the first place. Sherwin and his colleagues realized that there was significant and largely unexplored nuance to how a semiconductor’s electrons react to light. “This was unexpected,” he recalls. “But we decided to explore it further and started systematically looking at it.” In the new work, calculations done by postdoctoral scholar Qile Wu, a member of Sherwin’s team and co-lead author of the study, proved that this telltale sensitivity is more than a mere curiosity because it can be used to reconstruct the Bloch wave functions of holes in a semiconductor.

> **“This work is fascinating as a very fundamental demonstration of something you can do where the answer is really well defined.”**
> ***—Mette Gaarde***

The connection between the absorbed laser light and the emitted flash revealed itself in measurements of a property called polarization, or the direction in which light waves oscillate as they travel. In the experiment, the polarization of laser light influenced the phases of the wave functions of the running electrons and of their shadowy partners, the holes. When the reunion of the two produced light at the end of the experiment, the polarization of that flash was determined by these two wave function phases. Because such phases are typically represented as imaginary rather than real numbers in physicists’ equations, relating them to the very real and measurable polarization of light was a breakthrough for Wu and his collaborators. Shambhu Ghimire, a physicist at Stanford University, who was not involved with the work, underscores exactly this feature of the new study: it used light to obtain information that was previously seen as purely mathematical. “These [light-based] methods can sometimes be difficult or really conceptually challenging, but most of the time they provide access to this imaginary part of the complex number [wave function] that you do not have access to with other, conventional methods,” he says. Further, the team managed to reverse engineer whole Bloch wave functions from those same polarization measurements.

Ghimire further notes that the kind of laser light the U.C.S.B. researchers used is important beyond its polarization. They employed ultrafast laser pulses, hitting the electrons with light for as little as a trillionth of a second. Electrons in solids tend to bump into atoms instead of moving uninterrupted, so being able to control them with such celerity was crucial for the team to carry out its Peter-Pan-and-his-shadow manipulation of the electron and the hole. Otherwise, in any given run of the experiment, one or the other would likely slam into some atomic obstacle, preventing reunification. Seamus O’Hara, another co-lead author of the study and a Ph.D. student in Sherwin’s group, credits some of that technical advantage to the team’s use of U.C.S.B.’s state-of-the-art Free-Electron Lasers facility.

But the impact of the work will likely extend beyond specialized facilities and simple semiconductors. In gallium arsenide, Wu’s theoretical research showed, very few properties of the reemitted light have to be known for a mathematical reconstruction of Bloch wave functions. Other semiconductor materials may require more complete—and perhaps elusive—knowledge, however. “This work is fascinating as a very fundamental demonstration of something you can do where the answer is really well defined,” says Mette Gaarde, a physicist at Louisiana State University, who was also not part of the study. “But the implication is that you could potentially use this to learn something about more complex structures.”

The U.C.S.B. team is already making ambitious plans for next steps. Going forward, the researchers are interested in applying their technique to materials in which electrons strongly interact with one another or where laser light would excite particles more exotic than electrons and holes. “We’re looking for new materials. If people have semiconductors that they would like to have looked at, we’re excited to try,” Costello says, eager for more opportunities to glimpse the intangible world of wave functions many more times.

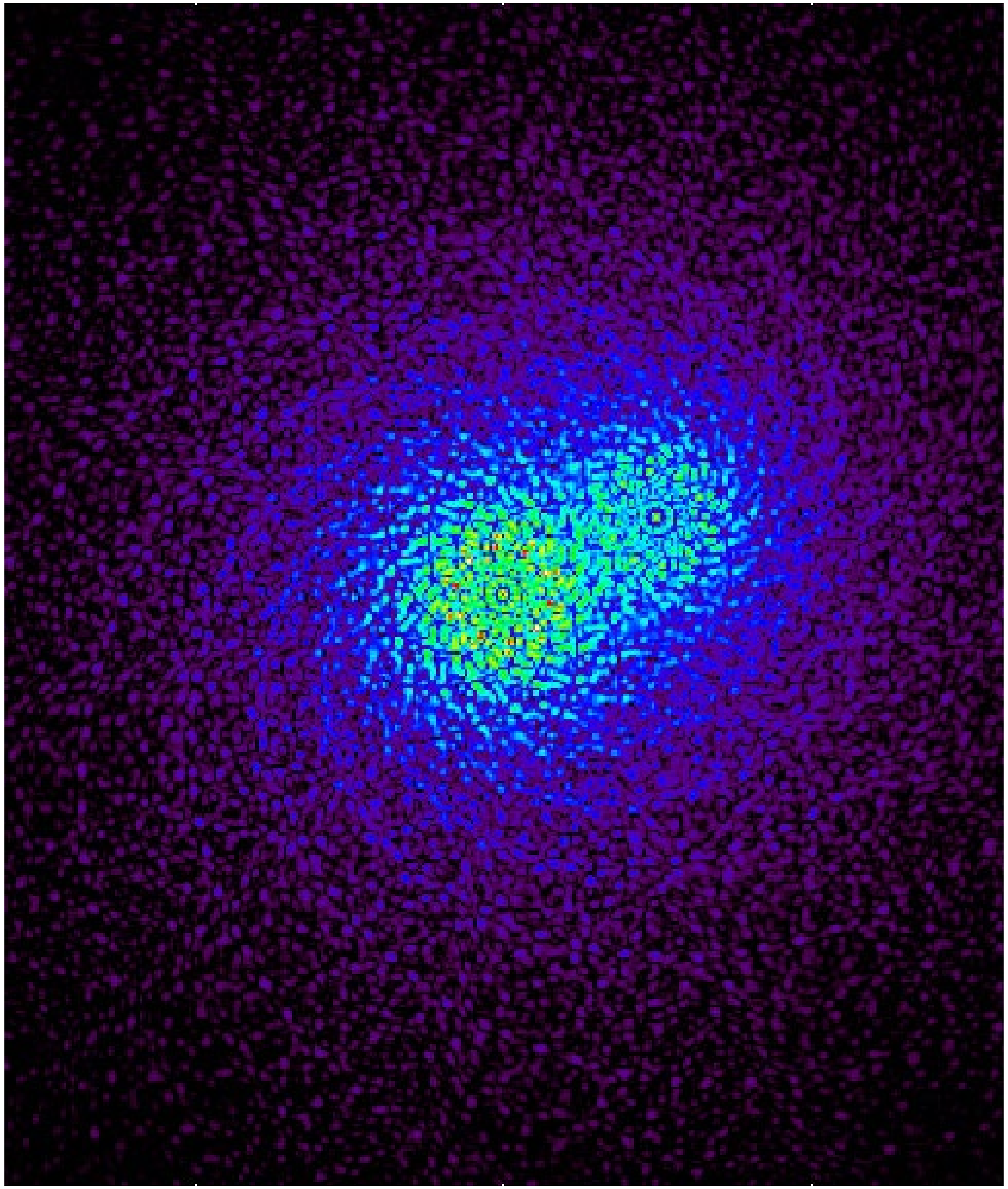
—Karmela Padavic-Callaghan

Scientists Plan Private Mission to Hunt for Earths around Alpha Centauri

A privately funded telescope called Toliman will seek habitable worlds in our nearest neighboring star system, potentially sparking a new wave of exoplanetary exploration

Do any habitable worlds exist in the closest stellar system to our own, Alpha Centauri? For years scientists have struggled to answer this question, unsuccessfully seeking to pierce the overpowering glare of the two sunlike stars, Alpha Centauri A and B, to see signs of orbiting planets (a third member of the system, the red dwarf star Proxima Centauri, is already known to possess at least one companion).

The scientific payoff for unveiling Alpha Centauri’s planetary retinue could be tremendous. At little more than four light-years away, a fraction of a stone’s throw in cosmic distances, these stars are tantalizingly close—right on our celestial doorstep.



Simulated view of what the Toliman telescope could see of the Alpha Centauri binary star system through its diffractive pupil.

Peter Tuthill/University of Sydney

Any planets there would be prime targets for further study, but Earth-like worlds potentially harboring life would be the grandest of all. Now a group of scientists plans to conduct a search for such worlds like never before, using a privately funded telescope to revolutionize our knowledge of Alpha Centauri. “We have this unique opportunity to reveal if there is a ‘habitable zone’ planet in the system,” says Olivier Guyon of the University of Arizona, part of the telescope’s team. “This is something that has never been done before.”

This relatively low-cost telescope, called Toliman, has secured funding of more than $500,000 from the Australian government to continue development, the team announced on November 16, 2021. Led by Peter Tuthill of the University of Sydney, who with his colleagues first devised the Toliman concept several years ago, the telescope has previously received backing from NASA’s Jet Propulsion Laboratory, space engineering firm Saber Astronautics in Australia, and the California-based Breakthrough Initiatives, funded by tech billionaire Yuri Milner. The small shoebox-sized telescope is being designed with a specific goal in mind: look for planets in the Alpha Centauri system, specifically any in its habitable zone, the starlight-warmed region in which liquid water could persist on a rocky world’s surface. It will do so in a way no other telescope can yet match. The aim is to finish and launch the telescope into Earth’s orbit by 2023, ready to begin its search from space. “This announcement is fantastic,” says Sara Seager of the Massachusetts Institute of Technology, a planet hunter unaffiliated with the project. “It’s just fantastic to see private foundations accelerating our search to find another Earth.”

> **“If we detect something, we hope that provokes a bit of a gold rush, and people will go after this with more sophisticated missions.”**
> ***—Peter Tuthill***

Many efforts have been made to find Alpha Centauri’s planets, with varying levels of success. In 2012 scientists thought they had found a planet orbiting Alpha Centauri B, dubbed Alpha Centauri Bb, but in 2015 other researchers seemingly ruled out the planet’s existence. Investigations of Proxima Centauri have proved more fruitful, revealing a possibly Earth-sized world dubbed Proxima b, and another planet—Proxima c—has also been hinted at. Earlier this year, meanwhile, a possible Neptune-sized world may have been found orbiting Alpha Centauri A.

Toliman, an ancient Arabic name given to Alpha Centauri but which also stands for the Telescope for Orbital Locus Interferometric Monitoring of our Astronomical Neighborhood, is designed to hunt for planets around Alpha Centauri A and B. Parts of the telescope are “already under contract” for construction, Tuthill says, while a precursor to the mission to test the technology, called Toliboy, was launched earlier this year on the CUAVA-1 satellite to the International Space Station. Lab testing and simulation work has been underway at the University of Sydney on the technologies for Toliman, Tuthill says, with the team now working on a full-scale prototype. Although some aspects of the mission are yet to be ironed out, such as its rocket ride to space and its station in Earth orbit, the technology itself is largely ready to go. “The components of this [telescope] are fairly mature,” says Guyon, who is also chair of the Breakthrough Watch project within Milner’s Breakthrough Initiatives, which has a goal of finding planets around Alpha Centauri and other nearby stars. “They can be made today.”

The telescope’s major trait is to make use of the binary nature of Alpha Centauri A and B, which are separated by slightly more than the Uranus-sun distance, to probe the existence of planets in either star’s habitable zone. The telescope will use a technology known as a diffractive pupil to study the stars, a transformative approach that employs “a bit of an optical trick,” Tuthill says. Rather than taking very high-resolution images of the stars, the 12-centimeter-wide telescope will spread the light from the stars into thousands of pixels, creating an elaborate patterned image within which a sort of photonic fingerprint of each star’s spatial position on the sky can be seen. From these data, the scientists hope to see minuscule shifts in each star’s position caused by gravitational tug of any orbiting planets. This task—a so-called astrometric measurement—is made much simpler by the presence of two stars rather than one, allowing the distance between the two stars to be more accurately measured. “Alpha Centauri is just a sitting duck for this particular technique,” Tuthill says. “It’s almost like the universe put it there for this particular mission.”

Two years’ worth of astrometric observations with Toliman should allow the team to tease out the presence—or absence—of planets orbiting at a similar distance to Earth; that is, within the habitable zone of Alpha Centauri A or of B. But astrometry’s greatest power is arguably its ability to give astronomers accurate measurements of any newfound planets’ masses by assessing the strength of each world’s gravitational pull on the stars.

Most other planet-detection techniques yield only estimates of mass, muddying the observational distinction between, say, a gas-shrouded “mini-Neptune” and a more Earth-like rocky orb. There are, however, minor downsides: Toliman’s studies will not initially reveal which of the two stars any such planets orbit. But we would know with near-certainty if any potentially habitable Earth-mass planets exist in the system. “We’ll be able to tell if it’s a habitable zone or an Earth-mass planet,” says Tuthill. “If we detect something, we hope that provokes a bit of a gold rush, and people will go after this with more sophisticated missions.”

The Toliman mission heralds interesting developments in exoplanet science. One is the use of private funds, rather than the sole backing from space agencies and other governmental institutions, to conduct space science off-world, focusing on a chancy endeavor with no guarantee of success. “Such high-risk missions have been hard to sell to public funding agencies because there’s a chance there is no planet in the Alpha Centauri system,” Guyon says, yet the potential rewards are great. “If there is something, we would know the nearest star system to us has a [potentially] habitable planet. It would completely change plans for agencies.”

The project also signals a much sought after shift, from finding thousands of exoplanets over the past two decades to studying certain star systems in lavish detail. “We’ve had this trend of finding so many planets,” Seager says. “But some of us in the community are ready to focus on individual stars.”

Emily Rickman of the Space Telescope Science Institute in Baltimore says the technology behind the Toliman telescope is “exciting” given the proximity of these stars to our own. “Finding any promise of alien life in our celestial backyard would be a really big deal,” she says.

Even if it does not detect anything, the mission will place useful constraints on the Alpha Centauri system. “If nothing is found, that will tell us either there’s something extremely tiny and close to the star that we cannot see or there’s nothing around those stars,” she says, which would be an intriguing and valuable result all on its own. Tuthill says there are secondary targets that could be examined after Alpha Centauri, also with the Toliman telescope, namely, other nearby binary systems such as 61 Cygni, which is 11 light-years away.

But none of these other stars are sufficiently close to afford as much precision, and thus could only be surveyed for heftier, probably less habitable, worlds. “We would hope to get down to super-Earths or Neptunes” in mass for detecting planets around those other stars, Tuthill says.

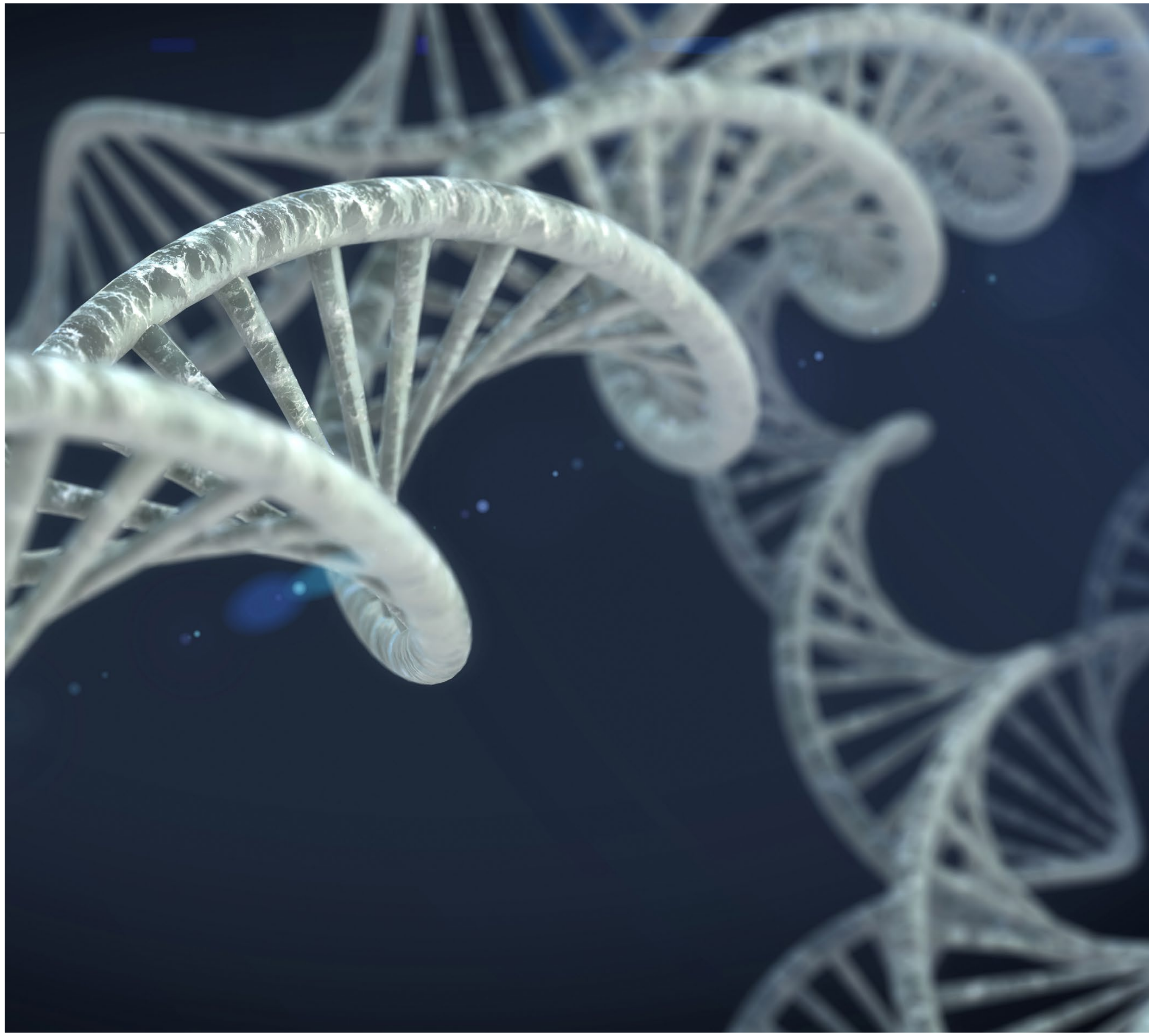
For now, however, Alpha Centauri is the primary goal, with the possibility of a titanic discovery on the horizon. Within just a few years we may know if one or more potentially habitable Earth-mass worlds exist there, so near at hand that we might seek not only to study them with telescopes but also to visit, reaching out via robotic probes launched across the interstellar depths. Proposals for such voyages already exist, including Breakthrough Watch’s more limelight-illumed kin Breakthrough Starshot, a sister project from the Breakthrough Initiatives aiming to send miniaturized spacecraft at perhaps a tenth the speed of light toward Alpha Centauri. Toliman would provide key data in support of such a multidecadal mission.

“We know there’s at least one planet in the system, Proxima b,” says Pete Worden, executive director of the Breakthrough Initiatives. “If we ultimately confirm that Alpha Centauri A and B do not have potentially life-bearing planets, then I would probably focus on Proxima.” If everything goes to plan, we may not have long to find out.

—Jonathan O’Callaghan

Life Is Complicated—Literally, Astrobiologists Say

A new theory suggests that searches for molecular complexity could uncover convincing evidence of extraterrestrial life—and do so soon



elsar77/iStock/Getty Images

The hunt for extraterrestrial life has always been bedeviled by false positives—those occasions where scientists think they've found life but turn out to lack a wholly convincing case.

The archetypal example comes from NASA's twin Viking landers, which delivered controversial evidence of life on Mars in the mid-1970s. That evidence was a whiff of radioactive carbon wafting from Martian soil, hinting at microbial metabolism taking place within—but three other life-detection experiments each lander carried only found null results. More muddled data about life on Mars arrived in 1996, when scientists discovered what could have been microbial microfossils inside a Martian meteorite found in Antarctica. But subsequent studies showed the putative microfossils could have easily been produced by several other entirely abiotic routes. Most recently, researchers studying the atmosphere of Venus claimed to see significant amounts of phosphine there—a gas that, on Earth, is chiefly made by microorganisms. Yet soon other scientists had cast doubt on the validity of those measurements, and had postulated the gas—if it was there at all—was from some strange but lifeless form of Venusian volcanism.

In each case, the pattern was the same: initial excitement, followed by subsequent skepticism, and eventual dismissal. Time and time again, it seems, astrobiologists are only finding alien signs of life—so-called biosignatures—that are frustratingly inconclusive. This is in large part because astrobiologists by necessity seek the simplest, most robust forms of life that appear possible in harsh otherworldly environments, and the chemicals and structures we often associate with such organisms on Earth can often be produced abiotically. And of course, the chemistry of alien life might be entirely different from what we observe on our own planet. Is there a better way to look?

A new theory published in *Nature Communications* contends that there is. Called assembly theory, it turns away from the search for simple chemical biosignatures, instead embracing life's fundamental complexity. It is based on the idea that any form of biology anywhere in the universe will encode life's information in complex assemblages of molecules that are measurably distinct from lifeless matter.

For study co-author Sara Walker, a biophysicist at Arizona State University, assembly theory is a landmark for the field because it "presents the first complexity measure that is testable in the lab." More broadly, she says, it gives us "the first glimmer of our ability to connect deep theoretical ideas about the nature of life to empirical observables."

In astrobiology, appeals to complexity have been on the rise for a while now. In light of the ambiguous results that can come from research focused on simple chemical signatures, scientists have developed theories and definitions of life that look to more sophisticated processes—metabolism, adaptation, replication, evolution—that could help us distinguish living systems from nonliving ones. In 1994, for example, NASA adopted a complex definition of life: "Life is a self-sustaining chemical system capable of Darwinian evolution." The trouble is, the key concepts behind such advanced frameworks are themselves complicated, making them notoriously difficult to test and quantify. Ask, for instance, five different evolutionary biologists for their working definition of "Darwinian evolution," and you are likely to get five slightly different answers. As NASA's chief scientist Jim Green, explains, "I can't build an instrument that is going to go out and find 'evolution,' 'reproduction,' or 'metabolism.' "

Assembly theory may offer a clearer, more general way to recognize life, whether familiar or alien. It builds on two related ideas: physical complexity and abundance, positing that as these two properties increase for any given object in any given environment, the chances of an abiotic origin decrease. Abundance tracks how often an object appears in an environment, whereas an object's complexity is measured by estimating the number of steps required for its assembly. Consider the difference between a seashore littered with water-worn pebbles—a situation that could easily be ascribed to a lifeless process—and one strewn instead with intricately sculpted seashells.

Although the theory is general and can pertain to many kinds of objects across a wide range of scales, the researchers looked at how it applies to molecules, arguably the most essential building blocks of biology that scientists can seek both in the lab and in space.

To rank molecular complexity, the team members created a mass assembly index, which algorithmically assigns a mass assembly (MA) number to different kinds of molecules. As a proof of concept, they used this approach to index and rank 2.5 million molecules in a widely used chemistry database. A molecule with an MA of 1 has low complexity and thus a higher chance of abiotic origins; more complex molecules are assigned higher numbers. Composed of one atom of phosphorus and three atoms of hydrogen, phosphine gas—the putative Venusian biosignature—merits only an MA of 1. In contrast, the amino acid tryptophan earns an MA of 12 thanks to its elaborate structure of 11 carbon atoms, 12 of hydrogen, and a pair apiece of nitrogen and oxygen.

According to Lee Cronin, a chemist at the University of Glasgow who led the research, this exercise revealed that at a certain threshold—circa MA 15—a molecule's probability of abiotic production in Earth-like conditions becomes astronomically low. Less than one in about 600 sextillion, in fact, Cronin says. Thus, molecules ranking at an MA of 15 or higher should almost always be made by life.

So does that mean that MA 15 is the surefire marker for life everywhere? No. For one thing, many low-ranking molecules can be biosignatures—such as the structurally simple molecular oxygen emitted into Earth's atmosphere by photosynthetic organisms. This means that although it may decrease the chances of false positives in the search for life, assembly theory also correspondingly raises the likelihood of "false negatives" allowing genuine biosignatures to slip through investigative cracks. More broadly, Cronin says, although MA 15 seems to be the threshold value for life on Earth, the threshold could fall elsewhere for wildly different planetary environments. The trick, Cronin argues, is to use assembly theory to map the gap that must exist between the chemical combinations produced abiotically and those produced by living systems—here or anywhere else.

To further validate their approach, Cronin and his colleagues double-checked their theoretical calculations of complexity by using mass spectrometry fragmentation to study a large sample of ranked molecules and substances, breaking each down into its constituent parts to confirm the number of chemical steps required to reassemble them. Those experimental results hewed closely to theoretical predictions and reliably distinguished between a broad range of living, nonliving and dead substances, including *E. coli* bacteria, yeast cells, plant alkaloids, ashes, coal, granite, limestone and even beer.

One of the most exciting validations came courtesy of Cronin's collaborator and study co-author Heather Graham, an astrobiologist at NASA's Goddard Space Flight Center. To conduct a test of the theory, Graham's lab sent a set of blind samples. One of these was preserved biological material from a multimillion-year-old fossil. Another was a sample from the Murchison meteorite, a bolide rich in organic (but abiotic) carbon compounds that fell to Earth in 1969. Cronin's testing flagged the Murchison material as notable for its wealth of complex molecules but still ranked it as below the threshold of MA 15 and thus lifeless. The fossil material, however, was identified as a signature of life.

For study co-author and NASA astrobiology postdoctoral fellow Cole Mathis, there was a striking moment at this stage of the research when a significant distinction became clear to all involved: the distinction between "a complex sample and a complex molecule." While a strange variety of chemicals like those present in Murchison might lead one to think that something like life was present there, it is actually the complex molecule, which indicates the organization of chemistry, that seems to be key to life.

The success of these results, and the publication of the work brought out initial excitement. Steven Benner, a chemist at the Foundation for Applied Molecular Evolution in Alachua, Fla., who was not part of the research, says he and his colleagues are "extremely enthusiastic" about assembly theory. Even so, he adds, Cronin and his colleagues still must address many unanswered questions about their work, especially whether it could actually be applied in "truly exotic environments."

Benner has challenged Cronin to test the approach on samples of "semicomplex" material that Benner's group has synthesized from simple carbon precursors in lab conditions mimicking the atmosphere of Venus. "This is a real environment," Benner says, "one soon to be visited in a space mission again. If Venusian life exists in the clouds above Venus, it would need to follow a chemical logic very much different from the logic that is followed by life on Earth." This, Benner says, arguably makes Venus the best site for a near-term test of the molecular-complexity metric.

In response, Cronin has remarked that Benner's samples pose a particular challenge because they are immersed in sulfuric acid—which decomposes organic molecules and thus lowers their detectable organic complexity. Nevertheless, Cronin says, "we are working on a way to reconstruct that complexity, so I remain hopeful that even in the most difficult samples, if the molecule is not broken, we can take a measurement."

In the meantime, Green and others at NASA have wondered whether assembly theory might be used to analyze data from the many mass spectrometers that have visited other worlds during the agency's various interplanetary missions. Green first considered the case of the mass spectrometer on the Cassini orbiter, which flew through and sampled plumes of water vapor venting from Saturn's icy moon Enceladus, but he realized that Cassini's instrument only registered masses up to 100 atomic mass units (amu), and assembly theory only works for molecules weighing at least 150 amu.

Although they could reach 150 amu and beyond, instruments on the Curiosity and Perseverance Mars rovers fell short, too, lacking the specificity to study single molecular species for an MA measurement. Future missions, Green says, should all be equipped with mass spectrometers that register the higher mass and take measurements with greater specification. There is promise for NASA's Dragonfly mission, a nuclear-powered quadcopter that is slated to begin exploring the atmosphere and surface of Saturn's moon Titan in the mid-2030s. Graham points out that Dragonfly's mass spectrometer, although it lacks some of the capabilities of lab spectrometers, will have the capacity to detect complex molecules.

In the future, other planned missions could seek out signs of life's molecular complexity at astrobiological hotspots across the solar system. Eventually, Cronin speculates, assembly theory might even be used to assess potential biosignatures remotely detected in the atmospheres of potentially habitable exoplanets by large telescopes.

For now, however, the approach has given theorists and experimentalists alike a wealth of new ideas for understanding—and seeing—life's cosmic complexity.

—Natalie Elliot

Heavy-Metal Exoplanet Found Orbiting Nearby Star

With a density close to that of pure iron, GJ 367b may be the remnant metal-rich core of an evaporated giant world

Five thousand known worlds. That is the next, most ballyhooed milestone in the ongoing hunt for exoplanets, the confirmed total of which currently tallies just a few hundred shy in our catalogs. More remarkable than these sheer numbers, however, is the diversity they reveal. A fraction of the worlds overflowing astronomers' coffers resemble those orbiting our own sun, but most are far more alien: scorched gas giants that circle their star every few days, Neptune-sized puffballs with the density of cotton candy, and hordes of small planets packed like sardines around tiny, cool stars. Compared with such things, our own familiar and supposedly typical solar system turns out to be the oddball.

The latest bizarre exoplanet to challenge our preconceptions and reinforce just how much we still have to discover is GJ 367b, a world so strange it seems more suited for a heavy-metal album cover or the pages of a pulpy sci-fi story rather than reality. Announced December 2, 2021, in the journal *Science,* this planet may essentially be a glowing orb of half-molten iron three-quarters the size of Earth.

Discovered by Kristine Lam of the German Aerospace Center (DLR) and her colleagues using NASA's Transiting Exoplanet Survey Satellite (TESS), GJ 367b is a peculiar "sub-Earth" world located relatively close by, around a small red dwarf star 31 light-years away from us. TESS's measurements showed the planet to be 9,000 kilometers wide—about a third wider than Mars—and subsequent observations using another facility, the European Southern Observatory's High Accuracy Radial Velocity Planet Searcher (HARPS), revealed it to be just half the mass of Earth. Taken together, these results imply an astonishing density—about eight grams per cubic centimeter, close to that of pure iron. "The planet is most likely to contain about 80 percent iron by radius," Lam

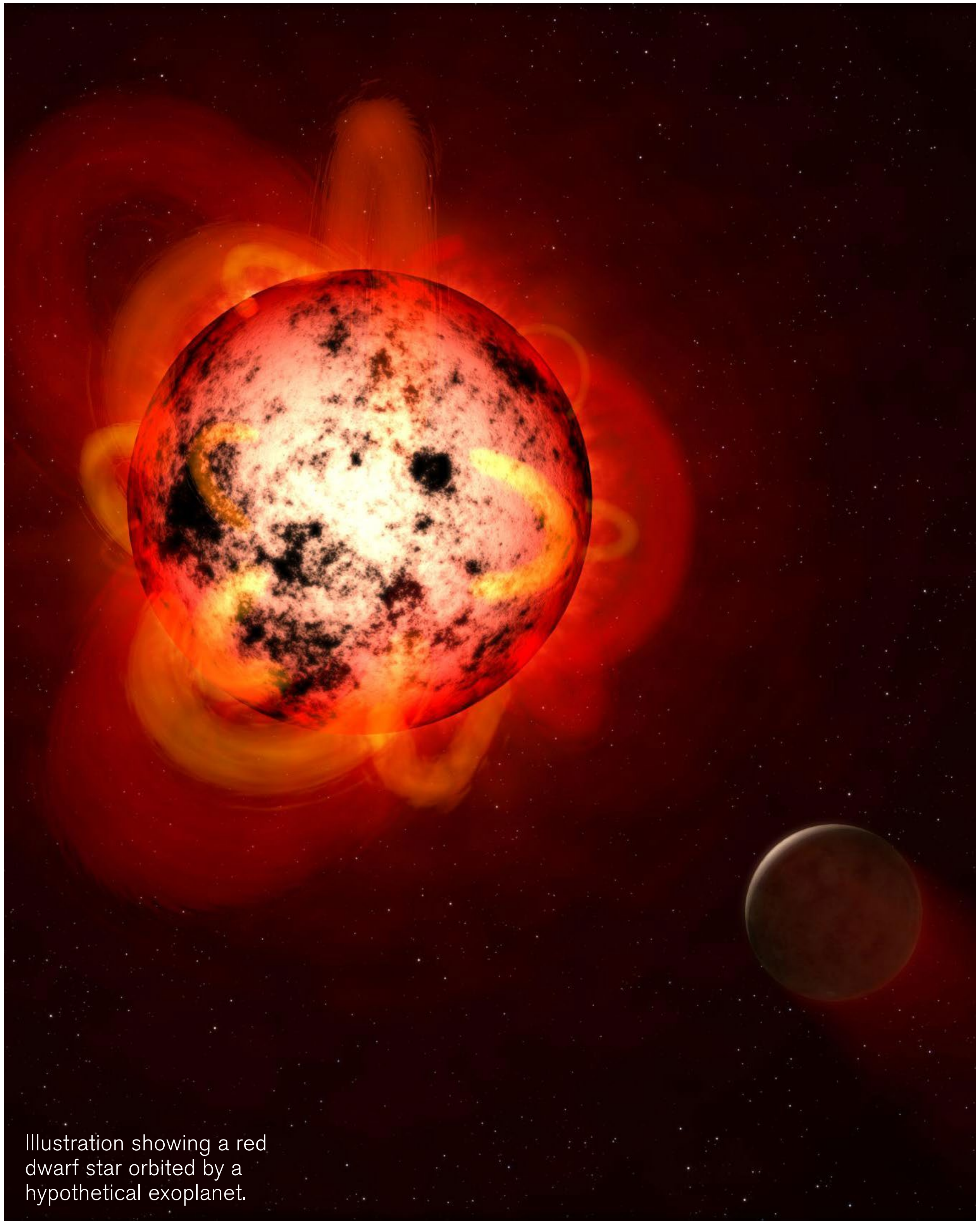


Illustration showing a red dwarf star orbited by a hypothetical exoplanet.

NASA/ESA/STScI/G. Bacon

says, with the rest of the planet encased by a rocky silicate mantle, a similar structure to Mercury in our solar system.

But unlike Mercury, which revolves 58 million kilometers from our sun in an 88-day orbit, GJ 367b is far closer to its star, completing an orbit in just 7.7 hours at a distance of only a million kilometers. That means the temperature of the planet's starlight-bathed surface could be as high as 1,500 degrees Celsius, enough to melt rock and metal alike. "It's probably not very pleasant to live on," Lam says.

About 100 of these so-called ultrashort-period rocky exoplanets have been previously found, but GJ 367b stands out among them as the smallest and least massive ever seen. Its proximity to its star means it is most likely tidally locked by gravitational effects, meaning it always presents the same hemisphere toward the star, much like the moon does to Earth. The enormous dayside temperatures may mean this half of the planet is covered in a magma ocean. "At those temperatures you expect your silicates to be in the liquid phase," says Alexandre Santerne of the Aix-Marseille University in France, who was not involved in this work but previously discovered another Mercury-like exoplanet. "It would be like a big magma pool." The nightside of the planet, meanwhile, would have vastly lower temperatures, meaning it "should be solid rock," Santerne says. At the terminator between night and day, you would expect "some transition between very cool rocks and the magma," he says. That difference could result in tempestuous winds if the planet has any semblance of an atmosphere, but most experts believe GJ 367b's extreme stellar proximity long ago rendered it airless.

How the planet reached its dismal state is a bit of a mystery that may carry important implications for our own solar system. The same gravitational forces that led to GJ 367b being tidally locked should have long ago disrupted the process of planet formation in the first place; planets are not thought to form extremely close to their stars. Instead they probably migrate inward from farther out—a process that can sometimes lead to spectacular interplanetary smash-ups when worlds literally collide. Similar giant impacts may have shaped our own Mercury, which perhaps was once somewhat more Earth-like in structure. "The best story, which is not a great story, is that some object smashed into Mercury and left behind a mostly iron object," says Joshua Winn of Princeton University, a co-author on the GJ 367b discovery paper. But this hypothesis is "a little uncomfortable because it invokes this collision for which we have no other evidence," he adds. "If we figure out why these iron-rich ultrashort-period planets exist, maybe there would be some connection to the story of Mercury."

One possibility is that rather than being the result of a cataclysmic collision, ultrashort-period rocky worlds such as GJ 367b could be the remnant iron cores left behind when stellar effects cook off the gassy envelopes of migrating giant planets. Astronomers' ever expanding exoplanetary census have found both giant "hot Jupiters" as well as GJ 367b–like worlds in very close orbits around stars. Yet notably absent from these extreme environs are Neptune-like worlds midway in size between the two. The reason could be that these worlds, pushed inward by another planet in the system, are then stripped of their hydrogen and helium atmospheres as they approach their stars, leaving only their rocky interiors behind. "It's quite conceivable [GJ 367b] was a bigger planet that has actually been fried away," says Lam's former professor Don Pollacco of the University of Warwick in England, who was not involved in the study. "You could imagine we're looking at the compressed core of an evaporated planet."

For Mercury, given its comparably greater distance from the sun, such an exotic origin story is unlikely. But further studies of Mercury, along with more observations and discoveries of ultrashort-period planets using next-generation facilities such as the James Webb Space Telescope, could get us closer to an answer of how such worlds come to be. More than anything, such work continues to highlight that, among the thousands of planets now known beyond our solar system, we continue to find strange and wonderful places. "We went looking for solar systems," Pollacco says. What we found instead and continue to find were worlds unlike anything we could have imagined.

—Jonathan O'Callaghan

After years of delay, the most ambitious observatory ever built has at last left Earth. It now faces a high-stakes series of deployments in deep space

By Richard Panek

Artist's impression of the James Webb Space Telescope folded and stowed inside its Ariane 5 rocket, shortly after launching from Europe's spaceport in French Guiana.

The James Webb Space Telescope Has Launched: Now Comes the Hard Part

ESA/D. Ducros

Richard Panek is the prizewinning author of *The 4% Universe* and the recipient of a Guggenheim Fellowship in Science Writing. His most recent book is *The Trouble with Gravity: Solving the Mystery beneath Our Feet* (Houghton Mifflin Harcourt, 2019).

THE RELIEF WAS AS DEEP AS the stakes were high. At 7:20 A.M. (ET) on December 25, 2021, the rocket carrying the largest, most ambitious space telescope in history cleared the launchpad in French Guiana, and the members of mission control at the Space Telescope Science Institute in Baltimore roared their elation.

The suspense was not quite over. Half an hour postlaunch, the telescope still needed to decouple from its host rocket, after which it had to deploy solar panels to partly power its journey. Only after that first deployment proved successful, said a NASA spokesperson in a statement to *Scientific American,* would "we know we have a mission."

Astronomers have more riding on the rocket than the James Webb Space Telescope (JWST). Also at risk is the viability of NASA's vast space science portfolio, if not the future of astronomy itself. As the successor to the Hubble Space Telescope (HST), JWST is one of those once-in-a-generation scientific projects that can strain the patience of government benefactors, as well as the responsible agency's credibility, but also define a field for decades to come—and possibly redefine it forever.

"This is a great day—not only for America and our European and Canadian partners, but it's a great day for planet Earth…. [JWST is] going to take us back to the very beginnings of the universe," said NASA administrator Bill Nelson in postlaunch remarks. "We know that in great reward, there is great risk. That's what this business is all about, and that's why we dare to explore. The James Webb Space Telescope is very much a part of that exploration."

As JWST separated from its rocket's upper stage, a video feed showed the now independent spacecraft gleaming in sunlight, capturing one last close-up look at the observatory before its quest to pierce the veil of cosmic darkness took it inaccessibly far from Earth. "When we look farther, delve deeper or measure more precisely, we're bound to find something wondrous," says Ken Sembach, the Space Telescope Science Institute's director. "Today we said goodbye to the telescope on the ground, and we opened our eyes to the universe."

The moment JWST's solar panels emerged, control of the mission officially shifted to Baltimore. For the Space Telescope Science Institute, says Massimo Stiavelli, head of the JWST mission office, "the easy part is done, and the hard part starts now." Then he laughs. "It's the best Christmas ever."

BACK TO THE BEGINNING

The telescope that would become JWST was already under discussion even before HST launched in April 1990. By orbiting Earth, HST would have a line of sight free of the optical distortions endemic to our planet's atmosphere. It would therefore be able to see farther across the universe (and, given that the speed of light is finite, farther back in time) than any terrestrial telescope.

Even so, HST would be observing primarily in optical wavelengths—the tiny portion of the electromagnetic spectrum that the human eye can detect. The Next Generation Space Telescope (as the future JWST was then known) would be looking at the universe in infrared, the regime into which cosmic expansion would have stretched, or redshifted, visible light emitted more than 13 billion years ago.

Much of the attention leading up to the launch has focused on the ability of JWST to peer farther into the past than HST, which has observed infant galaxies as far back as approximately 400 million years after the big bang. At that point in the universe's history, however, matter had already undergone several generations of evolution—galaxies merging and shredding, supernovae seeding space with additions to (what sentient beings on Earth would one day call) the periodic table of the elements.

JWST, however, will be able to see as far into the past as 100 million years after the big bang, a period when most matter consisted of only the primordial elements and was just beginning to coalesce into stars and galaxies. From the inception of JWST, the primary goal has been to glimpse these phenomena—the first luminous objects in the universe.

A NEW SEARCH FOR LIFE

The other major scientific frontier that JWST will probe is one that has received less attention but might prove to be just as profound in our understanding of the universe.

It is a bonus of sorts, a subject of study those 1980s-era visionaries could have scarcely foreseen: exoplanets.

Evidence for planets orbiting stars other than the sun first emerged in the 1990s (a finding that earned some of its discoverers a share of the 2019 Nobel Prize in Physics). Since then, astronomers have found exoplanets by the thousands, with tens of thousands more sure to overflow their catalogs in coming years. Almost all of these discoveries, however, rely on indirect evidence: the regular brightening and dimming of a star as a planet transits across its face or the wobble in a star's axis caused by the gravitational pull of a nearby world.

JWST should offer more direct evidence: observations of the planets themselves, a feat only a few other facilities can manage—though none with the promised clarity of this new space telescope. In visible light, the brightness of a star overwhelms any nearby objects, but by observing in the infrared, JWST will reduce the contrast so that the planets can pop out from the background stellar glare as tiny blips of light. That reduction in contrast will further help observers to probe the atmospheres of a handful of worlds for potential biosignatures such as oxygen (produced on Earth by photosynthetic plants), as well as tracers of habitability such as water and carbon dioxide.

In short: JWST offers some chance, however slim, to answer an eternal question: Are we alone?

"That's where the big discoveries will be," predicts Nicholas Suntzeff, an astronomer at Texas A&M University and former vice president of the American Astronomical Society. "Is there other life in the universe? If so, it would have to be the biggest discovery in science ever."

NEAR-DEATH EXPERIENCES

But first JWST will have to, you know, work.

Many of the members of the JWST project were not yet born when HST launched in 1990. But what happened next shadows them, just as it haunts all of NASA. Like some "Ghost of Missions Past," a grim event from the observatory's early days drags and rattles its chains along the otherwise pristine corridors of the Space Telescope Science Institute—the operations headquarters for HST and now mission control for JWST. Initial observations from HST were out of focus, and engineers soon realized that its mirror had been improperly polished, leading to a ruinous case of cosmic myopia and widespread public ridicule. Although spacewalking astronauts later repaired the mirror (at tremendous expense), the fiasco was a classic instance of "You had only one job," threatening to render HST almost useless and leaving NASA vulnerable to congressional oversight bordering on strangulation.

In the case of JWST, similar significant setbacks—technical, political, sociological—have preceded the launch. The original budget estimate was a hazy $1.5 billion to $3 billion, and its similarly nebulous launch date was, oh, let us say 2010. By that deadline, however, not only had costs risen to $5 billion, but much of the telescope was still on the drawing board. The development of JWST's myriad foundational new technologies was proving more intractable than planners had imagined. Only a year later the budget had ballooned by 60 percent to $8 billion—at which point Congress intervened, establishing a cost cap for JWST: $8 billion or bust.

Would Congress dare to cancel a scientific mission of such ambition? Yes, it would—and once did. In October 1993 President Bill Clinton signed a bill killing the Superconducting Super Collider, which would have been the world's most powerful particle accelerator. Never mind that the project had already cost $2 billion ($3.15 billion in 2021 dollars). Never mind that underground boring had already cleared nearly 19 of the projected 51 miles of tunnel. Never mind that the particle accelerator promised transformative scientific breakthroughs. Congress deemed the project's budget to be out of control. The cancellation blew a hole through the heart of the U.S. particle physics community, which, even three decades later, has yet to fully recover.

By 2018 the JWST project was both flirting with the congressional cap and pushing the launch date farther and farther into the future. Behind the scenes, as a Government Accountability Office investigation would later reveal, technical problems were multiplying: Workers at Northrop Grumman, the primary contractor for JWST, discovered that the application of an inappropriate solvent had damaged the observatory's propulsion valves. A wiring error destroyed the pressure transducers. And during vibration testing, dozens of bolts flew off the spacecraft.

The budget grew by another $800 million, officially exceeding the congressional cap. And the launch date slipped to 2021.

Even the name of the telescope has been a subject of controversy. In 2002 NASA's then administrator Sean O'Keefe announced that the Next Generation Space Telescope would thereafter be called the James Webb Space Telescope. The practice of replacing generic names for telescopes and observatories with the names of prominent scientists is routine. O'Keefe, however, violated two norms: His choice of honoree was essentially a unilateral decision, and that honoree was not a scientist but a fellow administrator—indeed, one of O'Keefe's predecessors. James E. Webb had served as NASA's chief during its race-to-the-moon heyday, from 1961 to 1968.

In recent years, though, the name of the mission has gained another layer of controversy: who Webb was at heart. Webb's tenure as the second in command at the Department of State in the late 1940s and early 1950s and then as the head of NASA coincided with what historians now call "the lavender scare"—a search for and purge of LGBTQ employees at these and other federal institutions. Investigations in recent years have turned up scant specific evidence of Webb's involvement, but the association between bureaucrat and bigotry is close enough that some astronomers insist on referring to the project only as "JWST" and never as "Webb."

WILL IT WORK?

Minor delays continued to plague JWST on its path to the launchpad. The launch date slipped repeatedly, first because of an accidental jostling of the telescope (an inspection revealed no damage) and then because of a flaw in a communication cable connecting the telescope to ground systems. On December 21, a forecast of high winds for Kourou, the launch site in French Guiana, nudged the timing of liftoff from Christmas Eve to Christmas Day.

JWST will still have to execute nearly 350 potentially fatal maneuvers— or "single points of failure" in NASA's nomenclature—while prepping for scientific observations. Perhaps trickiest of all will be the deployment of the mirror—or, more accurately, mirrors: 18 hexagonal gold-coated slabs in a honeycomb arrangement. Partly so that the telescope would not be too heavy to launch, engineers chose to make the mirrors out of the relatively lightweight element beryllium. But the weight of the mirrors was not the most difficult design challenge. It was their size.

When the mirrors assume their eventual configuration, they will collectively span more than 21 feet (in contrast to HST's eight-foot diameter), far too wide for a rocket's payload fairing. So engineers developed an ingenious solution: dividing the honeycomb into segments that fold up so that they fit inside the rocket on Earth, then unfold, origamilike, in space.

If all goes well, about 30 days after launch JWST will reach its final resting place (so to speak): a region of space that astronomers call the second Lagrange point, or L2, one of five sites in the solar system that 18th-century Italian-French mathematician Joseph-Louis Lagrange determined would keep pace with Earth in their orbits around the sun. At a Lagrange point, the gravitational balance between Earth and sun acts as a stabilizing influence, thereby allowing spacecraft to conserve fuel. (Other astronomical projects that have occupied L2 include the Wilkinson Microwave Anisotropy Probe and the Herschel and Planck space observatories.)

In the case of JWST, though, L2 has a further advantage: it is on the side of Earth directly opposite the sun, a position that reduces exposure not only to light but also to heat—an essential concern in an instrument sensitive to infrared wavelengths. Even so, JWST will still need thermal protection so that it can gradually cool down—across several months—to its operational temperature only tens of degrees Fahrenheit above absolute zero. Over the first week of its voyage, the telescope will unfurl a tennis-court-sized, five-layered sunshield (SPF one million) to separate its delicate optics and instruments from all the potential heat pollutants. On the telescope side of the shield, the temperature will approach –400 degrees F. On the other side, it may become as hot as 200 degrees F or more.

For all its advantages, though, L2 comes with one significant drawback: it is far from Earth—nearly one million miles, or four times the distance of the moon. HST enjoyed the benefit of human servicing missions—for instance, to fix the flaw in its mirror. But that option will not be available for JWST. If something breaks, it will stay broken.

But if nothing breaks, JWST will start streaming scientific data back to Earth this summer (NASA's collaborators on the mission, the European Space Agency and the Canadian Space Agency, will receive 15 and 5 percent of observation time, respectively). These telescopic treasures will contain not just new insights into the origins of cosmic structure and the atmospheres of exoplanets but also the secrets of star formation in the Milky Way and the geology of the outer planets in our solar system.

Only then will members of the worldwide JWST community be able to truly relax—and, for those who so wish, celebrate Christmas in July.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Dark Matter May Be Missing from This Newfound Galaxy, Astronomers Say

A growing number of galaxies seem to be bereft of the mysterious substance, posing fresh challenges for some of cosmology's most cherished theories

By Anil Ananthaswamy

Galaxy AGC 114905: Stars are shown in blue, whereas green denotes clouds of hydrogen gas. The galaxy does not appear to contain any dark matter.

Javier Román/Pavel Mancera Piña (CC BY 4.0)

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

Astronomers have found yet another ghostly galaxy that appears to be devoid of dark matter. Researchers have reported several such sightings over the past few years, each time flagging so-called ultradiffuse galaxies that can be as large as the Milky Way but relatively bereft of stars. This latest object, known as AGC 114905, is similar in size to our own spiral galaxy yet has 1,000 times fewer stars. If the dark matter–free status of AGC 114905 is ever confirmed, cosmologists will be forced to reexamine and perhaps even abandon some of their most cherished theories in favor of more exotic explanations for what makes up the universe's unseen mass.

"Different types of galaxies that are not exactly the same, measured with different techniques, seem to be telling a somewhat similar [story]," says Pavel E. Mancera Piña of the University of Groningen in the Netherlands, a member of the team that studied AGC 114905.

The story is one of outliers and stragglers that fail to conform to galactic norms. "It would be awesome if these strange objects ultimately give us information on the nature of dark matter," says Yale University astronomer Pieter van Dokkum.

AN INTERGALACTIC HUNT FOR DARK MATTER

Dark matter–free galaxies are anathema, especially because studies of galaxies that seemed to have copious amounts of dark matter are what led astronomers to posit that our universe is filled with it in the first place. For example, the speeds at which stars and gas in the nearby Andromeda galaxy are rotating around the galactic center suggest that much more matter must be present than meets the eye, providing the gravitational heft needed to keep the visible matter in orbit.

Such observations led to the Lambda-CDM (LCDM) model of cosmology, where Lambda refers to dark energy and CDM to cold dark matter, which is thought to make up about 27 percent of the universe. ("Cold" in this context merely means the putative particles of dark matter are moving far slower than the speed of light.) Simulations using cold dark matter have been extremely successful at replicating patterns seen in the large-scale clustering of galaxies, as well as in the cosmic microwave background, the leftover light from about 380,000 years after the big bang. But the predictions of these simulations for galaxy-scale goings-on have proved somewhat harder to reconcile with astronomical observations.

In LCDM simulations, galaxies form when dense clumps of dark matter in the early universe act as gravitational "seeds," sucking in even more dark matter to form massive halos onto which huge volumes of gas then coalesce, birthing stars. Thus, according to the LCDM model, all galaxies should have dark matter aplenty, with most of it tightly concentrated at galactic centers. But even before the discovery of these ostensibly dark matter–free ultradiffuse galaxies, studies of dwarf galaxies orbiting the Milky Way showed that these diminutive satellites lack the stark, central "cusp" of dark matter predicted by simulations. The dark matter distribution in these dwarf galaxies is smoother, forming a wider "core" rather than a sharp cusp at the center.

DRAGONFLY'S DISCOVERIES

In 2018 van Dokkum, Shany Danieli and their colleagues further muddied the waters with the discovery of an ultradiffuse galaxy called Dragonfly-2 (NGC 1052-DF2). The researchers found Dragonfly-2 using the Dragonfly Telephoto Array, an instrument designed to observe large and extremely faint objects in the night sky. They soon followed this up with the discovery of another galaxy called NGC 1052-DF4. Using a range of telescopes, including the Hubble Space Telescope (HST) and the 10-meter-class telescopes at the Keck Observatory atop Mauna Kea in Hawaii, van Dokkum and his colleagues measured the speeds of star clusters associated with these galaxies. From those speeds, they inferred each galaxy's total mass, finding that normal matter (in this case, mainly stars) is enough to explain the observations. Little if any dark matter is needed.

Many outside experts had doubts. "There was a big debate in our case," van Dokkum says. The controversy stemmed from uncertainties in their measurements of just how far these galaxies are from Earth, which helps constrain how much luminous normal matter they contain. Simply put, a galaxy's apparent brightness is influenced not only by its cosmic distance but also by the characteristics of its stellar population. Initial estimates put Dragonfly's odd pair at a distance of about 20 megaparsecs—that is, more than 65 million light-years. But if the galaxies were instead considerably closer—perhaps only 13 megaparsecs away rather than 20, as one follow-up study suggested—their apparent brightness could be better explained by smaller amounts of luminous normal matter. The speeds of the associated star clusters would then require greater fractions of dark matter in both NGC 1052-DF2 and NGC 1052-DF4.

But in April 2021 van Dokkum's team released the results of an in-depth HST study of both anomalous galaxies, showing that their greater initial distance estimates were correct. If anything, the galaxies are a wee bit farther away, making the case for little or no dark matter even stronger. "This convinced people and, frankly, ourselves," van Dokkum says.

For NGC 1052-DF2 and NGC 1052-DF4, or DF2 and DF4, the evidence is clear: these two galaxies lack dark matter. But because both reside near a massive elliptical galaxy, called NGC 1052, the explanation may be simple: their dark matter could have been "tidally stripped" away by the gravity of this humongous companion, leaving behind only the normal matter.

Some astrophysical processes could hasten such outcomes. In March 2021 astrophysicist Marta Reina-Campos of McMaster University in Ontario and her colleagues showed how certain types of small, dense dark matter halos forming in the early universe could give rise to great clusters of massive stars near a young galaxy's center. As these stars expired in explosive supernovae, the resulting winds and shocks would drive outflows of dark matter away from the galactic center. "That would eventually expand the [dark matter] halo, creating a core in the center and lowering its concentration," Reina-Campos says. Add to that tidal stripping, and DF2 and DF4 no longer seem so mysterious.

"The observation suggests that there is no room for dark matter."
—Pavel E. Mancera Piña

SIX STRANGE SINGLETONS

But the newfound object AGC 114905 adds an entirely new twist to this complex cosmic tale. In 2019 Mancera Piña and his colleagues reported their discovery of six ultradiffuse gas-rich galaxies, made using the Very Large Array (VLA) radio telescope in New Mexico. The VLA observations revealed that gas clouds in these galaxies are orbiting much slower than would be expected if the galaxies harbored typical amounts of dark matter. The initial low-resolution measurements suggested that the clouds' speeds could be explained by the presence of normal matter alone. Also, unlike the pair of DF2 and DF4, each of these galaxies is a singleton, isolated and nowhere near any other cosmic object that could strip away dark matter. Other astronomers were intrigued but still skeptical because the VLA observations were not strong enough to support definitive conclusions. "Everyone was saying, 'Okay, but now you need better data to fully convince us,'" Mancera Piña says.

AGC 114905 was the one galaxy out of six that the team chose for deeper investigation. Mancera Piña and his colleagues observed the galaxy for 40 hours, using a high-resolution configuration of the VLA. Previously, they had studied the galaxy's rotation by looking at the speeds of gas at two locations along its radius; this time they looked at five. The results did not change. "The observation suggests that there is no room for dark matter," Mancera Piña says.

The latest observations of AGC 114905 also disagree with predictions from theories of modified gravity, such as modified Newtonian dynamics (MOND). Such theories seek to explain the motions of stars and gas in galaxies without resorting to dark matter. "[MOND] tells you directly how the galaxy should rotate," Mancera Piña says. "And this prediction is completely off of our value."

Stacy McGaugh, an astronomer and long-time proponent of MOND at Case Western Reserve University, is not convinced. "This is one galaxy. As such, using it to make strong claims—they claim to falsify both LCDM and MOND—is overstating the case," he says. "The normal behavior of galaxies is well established. That this is an outlier is more likely to be due to systematic uncertainties rather than a real physical effect."

A DOUBTFUL INCLINATION

Mancera Piña and his colleagues acknowledge that the biggest sources of uncertainty in their observations are their reckoning of the galaxy's overall shape, plus its inclination angle—how tilted it is with respect to our cosmic line of sight. This angle has an outsize influence on estimates of just how fast things are whirling about within a far-off galaxy. For technical reasons, astronomers can currently only measure how fast a galaxy's stars and gas are moving toward or away from us; any lateral motion in the plane of the sky is impossible to discern for distant galaxies. A spiral galaxy seen face-on (with an inclination of zero) would yield essentially no information about the velocities of its stars, whereas one seen edge-on (with an inclination of 90 degrees) would allow very accurate measurements of stellar speeds. Hence, an accurate estimate of a galaxy's inclination is crucial.

The team took AGC 114905 to be circular and estimated its inclination to be about 32 degrees, plus or minus three degrees. Yet, Mancera Piña says, "if you want both MOND and cold dark matter to work, that inclination will need to be around 10 degrees, so the galaxy will need to look rounder. We have measured this as carefully as possible. And we find that the associated uncertainties of our measurement are very far away from those 10 degrees."

If the assumptions about the galaxy's circular shape were off—because it is oval or distorted or has some other weird shape—then this, too, would impact the inclination estimate and thus the estimated speeds of stars and gas. "This is a systematic that always leads one to overestimate the inclination," McGaugh says.

Studying the galaxy with an optical telescope rather than the radio-based VLA would help reduce the uncertainty, van Dokkum says. "I hope somebody gets a Hubble image of this object," he says. "Then we can see what it actually looks like." Meanwhile Mancera Piña and his colleagues are planning to use the VLA at high resolution to scrutinize the other five ultradiffuse galaxies from their initial study that have also shown similar characteristics.

Benoit Famaey, an astronomer at the Strasbourg Astronomical Observatory in France, argues for studying an even larger sample of such galaxies to rule out any systematic bias arising from imperfect inclination measurements. "We have very good reasons to doubt the inclination measurement, which is the key to the result," he says. "We should therefore wait for a larger sample size of such a putative galaxy population before throwing all our present theories of galaxy formation [into] the trash can."

Still, he concedes that if the results are verified, the implications would be enormous. "Assuming it holds, the authors are totally right to think it poses a problem to both LCDM and MOND," Famaey says.

If that happens—and this is a big if—the focus would shift to other candidates for dark matter. That is because the favored explanation for DF2 and DF4—that they were somehow stripped of their cold dark matter—does not work for AGC 114905, given its isolation in space.

DARK MATTER DIVERSIFIES

One promising alternative to cold dark matter is something called self-interacting dark matter (SIDM). In the LCDM model, dark matter is considered collisionless, meaning it does not interact with itself. But if particles of dark matter can routinely collide and interact with one another, this could help explain the diversity of distributions of dark matter observed in different galaxies.

In a study published in 2019, Manoj Kaplinghat of the University of California, Irvine, Hai-Bo Yu of the University of California, Riverside, and their colleagues showed that self-interacting dark matter would redistribute kinetic energy from the outer regions of a galaxy's dark matter halo to its inner regions on cosmological timescales. Collisions between dark matter particles would, on average, increase the velocities of those nearer the galactic center, making them gradually spread outward to transform the dark matter density profile from a cusp into a core. The team showed that the observations of the orbital speeds of stars within galaxies of a number of different types, as captured in the Spitzer Photometry and Accurate Rotation Curves (SPARC) data set, is better explained with models of self-interacting dark matter than with LCDM.

In 2020 Yu and his colleagues showed self-interacting dark matter could enhance the tidal-stripping effects postulated to have removed the mysterious substance from DF2 and DF4. "The effect of self-interactions is to push the dark matter from the inner regions to the outer regions [of the galaxy]," Yu says. Once this happens, a nearby behemoth such as NGC 1052 can take over, siphoning away the dark matter from the outer regions of DF2 and DF4. The same scenario is far more unlikely if one assumes collisionless cold dark matter.

But given that AGC 114905 has no nearby neighbor to explain its potential lack of dark matter, Yu and Kaplinghat, along with Mancera Piña and their colleagues, are trying to see if starting with a different initial halo of dark matter (than is usually assumed in LCDM) can provide some answers. Simulations throw up many types of dark matter halos, and cosmologists take as their starting point the likeliest halo type as the basis for further analysis. But galaxy formation could possibly begin with other types of halos that have a different distribution of dark matter. "We are exploring some dark matter halos … that no one has explored before. We see some promising signals," Yu says. "We will study 'dark matter–free' ultradiffuse galaxies in both CDM and SIDM frameworks to see which one agrees better with the observations."

Subir Sarkar of the University of Oxford endorses using any and all means to make sense of dark matter. "The landscape of theoretical candidates for dark matter is very rich, and we have had little guidance so far, either from accelerator experiments or from direct or indirect searches, to narrow down the possibilities," he says. "Any indication that dark matter has self-interactions is very interesting as this immediately argues against popular candidates like [CDM]…, as well as against MOND. So the importance of these observations and the need for better understanding of galaxy formation with such nonstandard dark matter cannot be overstated."

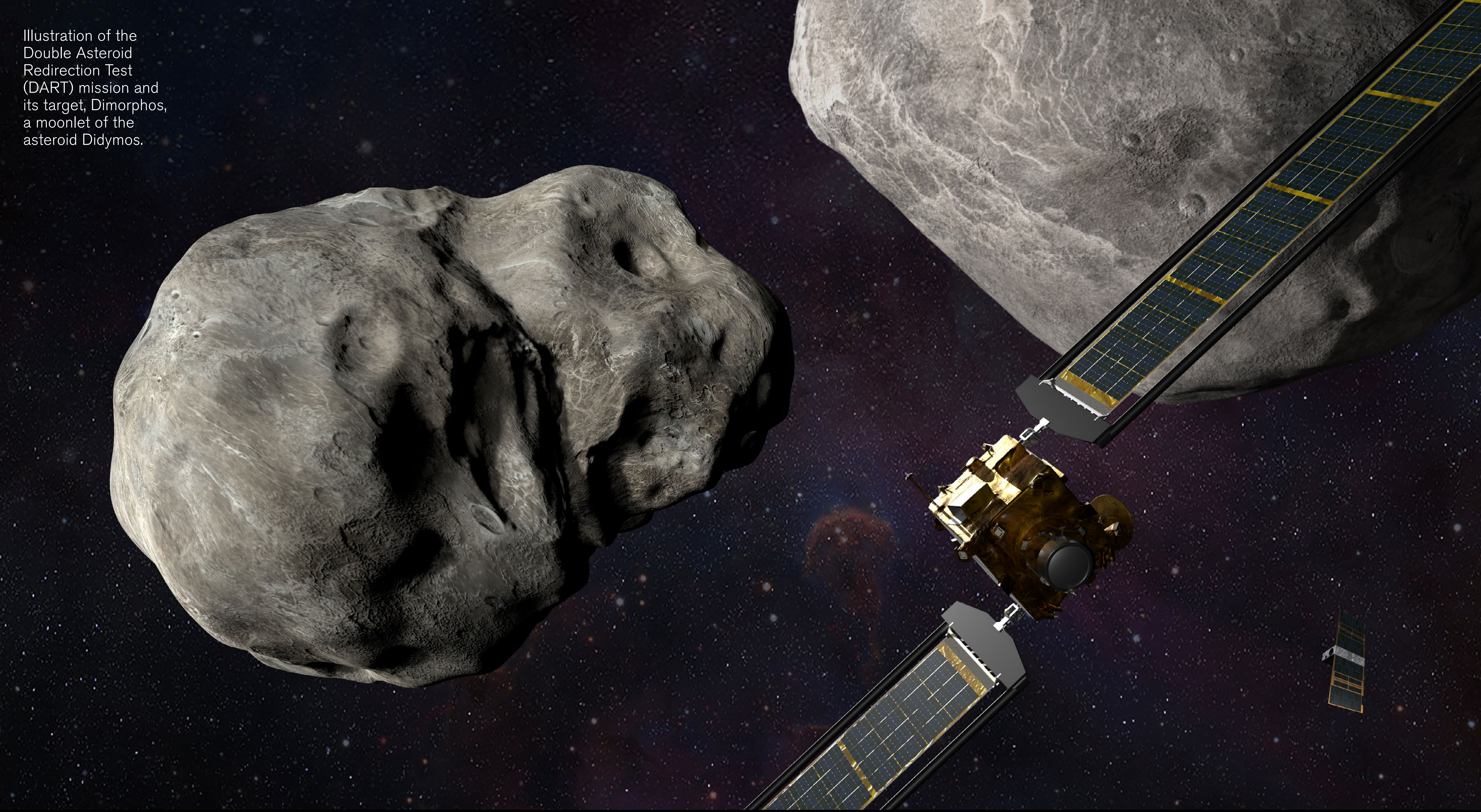

Illustration of the Double Asteroid Redirection Test (DART) mission and its target, Dimorphos, a moonlet of the asteroid Didymos.

NASA/Johns Hopkins APL/Steve Gribben

NASA's DART Mission Could Help Cancel an Asteroid Apocalypse

Our planet is vulnerable to thousands of "city killer" space rocks. If–when–one is found on a collision course with Earth, will we be ready to deflect it?

By Robin George Andrews

Robin George Andrews is a volcanologist and science writer based in London. His most recent book is *Super Volcanoes: What They Reveal about Earth and the Worlds Beyond* (W. W. Norton, 2021). Follow Robin George Andrews on Twitter @SquigglyVolcano

BACK WHEN ANDY RIVKIN WAS IN COLLEGE, HE HAD A FEW FRIENDS IN MEDICAL SCHOOL. "I WAS LIKE, oh, man, I don't want do anything that has too much responsibility," he says. Instead he looked to the stars. "Astronomy seemed pretty safe." And, for a while, it was. Rather than having to make decisions about someone's root canal or abdominal surgery, he watched worlds flit about in the darkness.

But Rivkin, a planetary astronomer at the Johns Hopkins University Applied Physics Laboratory (APL), has found himself with more responsibility than he expected. Along with hundreds of others, he is part of the Double Asteroid Redirection Test (DART) mission, an ambitious effort led by NASA and the APL to slam an uncrewed spacecraft into an asteroid to change its orbit. This is a dry run for the real deal: one day a technological descendant of DART could be used to deflect a planet-threatening space rock, saving millions—perhaps billions—of lives in the process.

On November 24, 2021, DART launched on a SpaceX Falcon 9 rocket from California's Vandenberg Space Force Base. Sometime next fall, it will smash into its target at 24,000 kilometers per hour. Ground-based astronomers like Rivkin will watch the rendezvous unfold with bated breath, hoping to see the telltale signs of success: a dust cloud and an asteroid dancing to humanity's tune for the very first time. Will it work?

"We do not know what's going to happen, because we have never tried it before," says Michele Bannister, a planetary astronomer at the University of Canterbury in New Zealand.

Success would not mean Earth is automatically protected from rogue asteroids. Despite resting most of our homeworld-protecting hopes on shooting at space rocks, there are no silver bullets in planetary defense. The bizarre and variable geology of asteroids may serve to rebuff our deflection attempts, our network of early-warning telescopes is rife with gaping observational holes, and the politics of deciding who can try to deflect an inbound impactor are fraught with uncertainty.

DART, no doubt, represents a major step forward. But the path to a comprehensive planetary defense plan is a long and winding road, and we have just begun to walk it.

NIXING THE NEXT TUNGUSKA

Despite the prominence of Texas-sized asteroidal antagonists in Hollywood blockbusters, big rocks are not a cause for much concern among levelheaded scientists. Almost all asteroids a kilometer or larger across with orbits approaching Earth have already been found, and none shall seriously threaten us in the next few centuries.

Like much in life, when it comes to planetary defense, it is the small things that matter. The space rock that exploded in midair over the Russian city of Chelyabinsk on February 15, 2013, was estimated to be just 17 meters long—and yet its blast, equivalent to perhaps 470 kilotons of TNT, unleashed a window-shattering shockwave that injured 1,200 people.

This airburst event, the first of its kind in the social media age, caused jaws to drop across the world. "It was sobering," says Kelly Fast, the Near-Earth Object Observations Program Manager for NASA's Planetary Defense Coordination Office—an office set up, not coincidentally, just three years after the Chelyabinsk event.

It could have been worse. In 1908 what seems to have been a 60-meter meteor detonated above a remote stretch of Siberia, flattening more than 2,000 square kilometers of forest. Imagine that happening over the city or town you live in: buildings would be reduced to rubble, debris would fly about in hurricane-force winds, and clothing and flesh alike exposed to the initial, scorching flash could burst into flames. It would be comparable to a massive nuclear explosion, minus the radiation.

These small impactors are disconcertingly plentiful. Of those at least 140 meters across, models suggest around 25,000 exist that approach within 190 million kilometers of the sun. Some of these so-called city-killer objects may pass unnervingly close to Earth's orbit. And of these diminutive but destructive near-Earth objects, "we think we've found fewer than half," Rivkin says.

It is estimated that, every century, there is a 1 percent chance a city killer will impact Earth. Even if that transpires, most of the planet's surface is ocean, suggesting that a space rock is most likely to land in the middle of nowhere. But if one of them hits any nation, plunges into a country's coastline or blows up overhead, it could

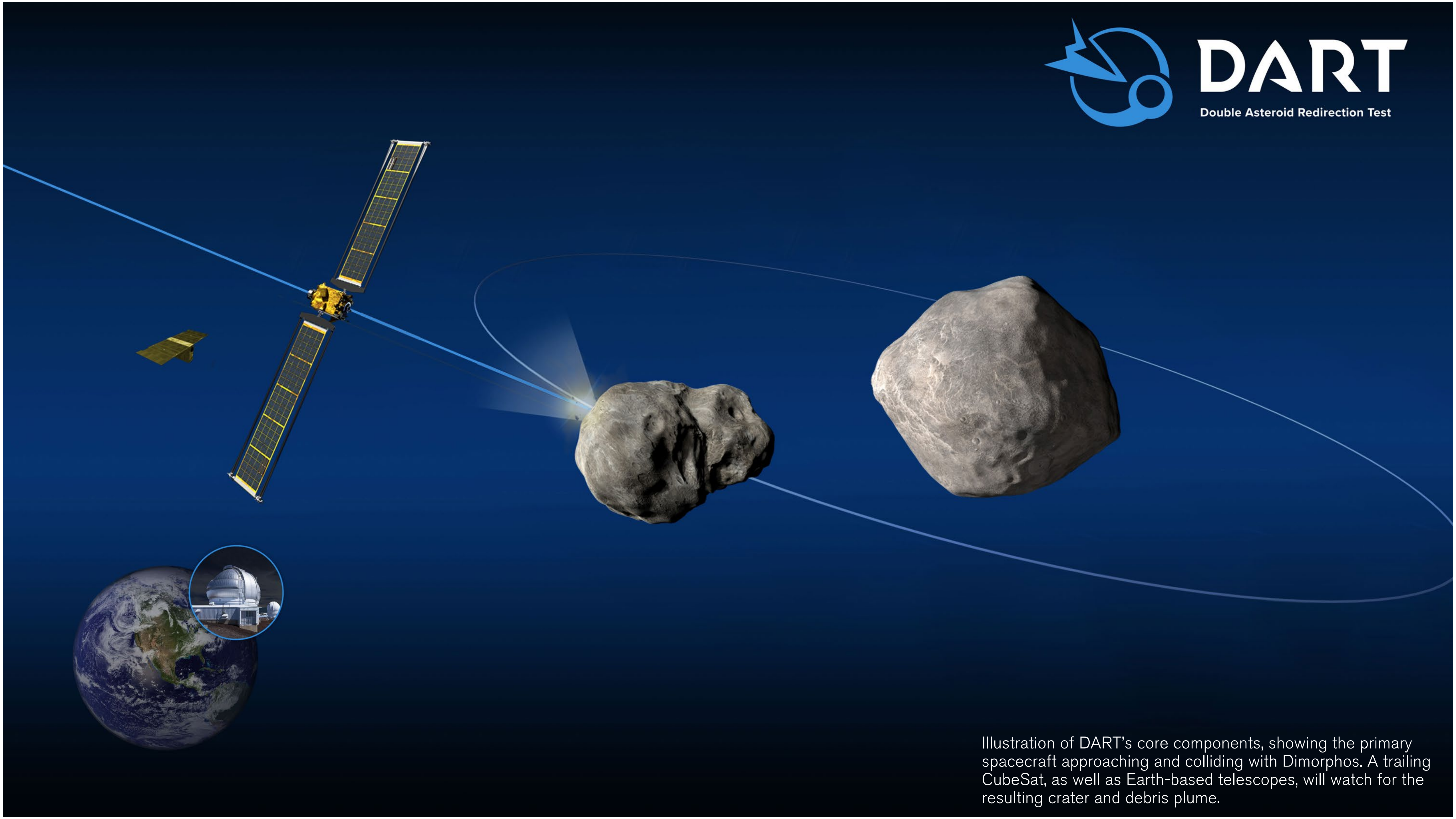

Illustration of DART's core components, showing the primary spacecraft approaching and colliding with Dimorphos. A trailing CubeSat, as well as Earth-based telescopes, will watch for the resulting crater and debris plume.

NASA/Johns Hopkins APL

cause one of the worst natural disasters in human history. Any given year, the odds are on our side, but wait long enough, and our luck will run out. Without an effective defense plan, "it's not a matter of if but when" a city killer will make our global civilization have a very, very bad day, says Kacper Wierzchoś, an astronomer at the University of Arizona.

Hollywood's preferred defense solution—nuclear bombs—probably could work, as high-fidelity simulations have shown that a sufficiently powerful blast could either knock an asteroid out of Earth's way or tear it into harmlessly tiny pieces. Using nukes to deflect or disrupt an asteroid, however, is widely considered to be a red-tape-wrapped last resort, a desperate Hail Mary lobbed toward an imminent threat that astronomers detected far too late for other more subtle interventions to suffice. "A kinetic impactor is what we think of right now as our top solution," says Cristina Thomas, a planetary astronomer at Northern Arizona University—in other words, using a speedy but inert projectile to deflect an asteroid many years in advance.

Scientists have simulated playing billiards with asteroids countless times. But there is only one way to know for certain whether we can fling one out of Earth's way: venture into the darkness, find an asteroid and give it a good thwack.

HUMANITY VS. DIMORPHOS

DART, a car-sized box with two winglike solar panels, will soon be heading toward a binary asteroid system. Didymos, nearly 800 meters across, is orbited by a moonlet, Dimorphos, which is 160 meters long. That little moonlet is DART's target.

About a month out, Didymos will just barely register in DART's camera. Four hours prior to impact, the spacecraft's guidance system—a technological cousin of those used to steer missiles on Earth—"takes the wheel and guides us in," Rivkin says. Shortly thereafter, Dimorphos will swim into view as a blurry but distinct speck of light. About two minutes out, Rivkin explains, the autonomous pilot "takes its hand off the wheel and its foot off the brakes."

DART will take and transmit snapshots of its rapidly approaching final destination until the very last instant, before disintegrating into a cloud of shrapnel and superheated plasma in an epic—but entirely noiseless—collision. In space, no one can hear you go "boom."

Ideally, DART's momentum gets transferred to Dimorphos, leaving behind an impact crater and shifting the moonlet's almost 12-hour orbit around Didymos by at least 73 seconds. A pint-sized CubeSat, released by DART 10 days prior, will observe the violence up close, while ground-based astronomers keep an eye on the binary asteroid system from afar until it fades from view in spring 2023.

Astronomers cycled through several target candidates for DART but settled on Dimorphos for several reasons. The first is one of safety: changing Dimorphos's orbit cannot change the orbit of Didymos to put it on an intersecting path with Earth. The second is that Dimorphos is a bit like the hand on a massive clock, with Didymos in the clock's center; despite being hundreds of millions of kilometers away, astronomers on Earth will be able to easily see if the "hand" is ticking around the clock differently postimpact. Just two months of observations will reveal how effective the deflection has been. Dimorphos is also in the size range of asteroids that can squash entire cities, putting it in "the sweet spot from a planetary defense perspective," Thomas says.

DART is an odd endeavor by any standards, a brief candle purpose-built for snuffing. Unlike the typical interplanetary mission, which lasts many years, it will operate in space for just 10 months. No extensions await it because DART "has a very definite end," says Elena Adams, the mission systems engineer on DART at APL. "In this case, if you keep it going"—in other words, if the spacecraft misses its target—"you really messed up."

The most distilled definition of success here, then, is simply hitting the target and measuring the shift in Dimorphos's orbit. But what if Dimorphos refuses to play ball?

THE MANY DEVILS OF DEFLECTION

On Independence Day, 2005, NASA's Deep Impact spacecraft fired a projectile into Comet Tempel 1, generating a fireball and giant debris plume that allowed scientists to glimpse the interior of a cometary nucleus for the first time. Humanity's attack run on Tempel 1 found that cometary nuclei can be remarkably fluffy, a notion bolstered by the European Space Agency (ESA) vehicle Philae's 2014 landing on another rather puffy comet, 67P/Churyumov–Gerasimenko. Such low-density targets pose a problem for planetary defense. "How do you push something like that? How do you fight with foam on a beach?" Bannister says.

Asteroids, too, hold disquieting structural surprises. When NASA's OSIRIS-REx spacecraft briefly touched down on the asteroid Bennu in 2020 to grab some rock samples, it almost sank into the target spot as if the surface was made up of "melted butter," says Patrick Michel, principal investigator of Hera, a follow-up ESA-led mission, slated to arrive at Didymos in 2026 to examine DART's consequences up close. Asteroids lacking sufficient gravity to squeeze their innards—perhaps including those city killers one kilometer or less in size—could be like "rocks flying in formation," Bannister says. This perversely means that in many respects small space rocks are harder to deal with than large ones, in which gravity's heavy hand overwhelms most material properties. So, when trying to deflect a city killer, Bannister says, perhaps we should be thinking: "How do you move a school of fish, not: how do you throw a mountain?"

All of this is pertinent to DART. Megan Bruck Syal, a planetary defense researcher at Lawrence Livermore National Laboratory, has repeatedly simulated its fated impact. "On the surface, the DART experiment seems really simple," she says. But only one thing is certain: no outcome is assured because so many of Dimorphos's fundamental properties remain unknown.

Mission planners are reasonably confident that DART's hushed demise will successfully convey a billiardlike kick to Dimorphos, which seems hefty enough to be sufficiently squeezed by gravity's clutches. But in the case of a slightly less substantial object, a kinetic impactor could just shoot right through, like a bullet through a cake, blowing it into small but still dangerous chunks. A successful deflection for such threats could require multiple, more gentle impacts rather than a one-and-done wallop.

Another huge unknown is Dimorphos's appearance. It could be shaped like a potato, a dog bone, a rubber duck, two bowling balls stuck together, or something else entirely. A colleague recently gifted Adams a doughnut-shaped

Workers within a clean room at the Johns Hopkins University Applied Physics Laboratory prepare the DART spacecraft for shipment to its launch site at Vandenberg Space Force Base in California.

NASA/Johns Hopkins APL/Ed Whitman

fridge magnet, a wink to how often asteroids surprise scientists once unveiled up close by some deep-space robotic emissary. A near-spherical or even potatolike shape would be optimal for a clean hit, whereas the uneven distribution of mass from more complex morphologies would raise the chance of a glancing blow, one that could just "spin up the moonlet and not actually change its orbit," says Olivier de Weck, a systems engineering researcher at the Massachusetts Institute of Technology.

In the specific and benign case of Dimorphos, all these uncertainties are mostly academic. But in the event of a deflection attempt for a true city killer, they could prove critical. We could, for instance, successfully deflect a potentially hazardous asteroid only to inadvertently put it on a new orbit that makes it more likely to hit Earth in the long run. There are points in space around our planet known as gravitational keyholes, wherein Earth's pull on the asteroid sets the errant space rock on an assuredly destructive journey. "Once you go through a keyhole, the probability of hitting Earth is virtually 100 percent," de Weck says. This, to put it mildly, constitutes a major hurdle for any preemptive strikes against nascent impact threats.

FOREWARNED IS FOREARMED

The emerging calculus is formidable indeed: protecting ourselves from the most numerous and tricky (and thus most dangerous) space rocks requires more than making shots in the dark, especially when each "shot" is a multimillion-dollar deflection attempt. Ensuring success requires first scouting out the threat to learn any given space rock's exact mass and ability to absorb a weighty impact.

Some of that work can be done from Earth, but as Dimorphos is deviously demonstrating, tiny objects are hard targets for remote studies. It is far better—albeit more difficult—to get up close and personal with any adversarial asteroid before trying to hit it at all. This was, in fact, ESA's original plan, before schedule slips ensured that its reconnaissance spacecraft would arrive only after DART's dramatic impact. In the future, miniaturized kinetic impactors could even be sent alongside scientific scouting missions, meant to merely nudge target asteroids to estimate how they would respond to more powerful deflective blows. "We have to go and characterize them better before we rest humanity's fate in that one golden shot," de Weck says.

Such precursor missions are only possible if a malevolent asteroid is spotted many years prior to its Earth impact date. Which adds spine-chilling urgency to astronomers' overlooked and underfunded efforts to find the missing half—or more—of our solar system's population of city killers. And whereas current facilities and the next-generation Vera C. Rubin Observatory are up to this task, they might not be for much longer given the seemingly unstoppable proliferation of satellite mega constellations, whose sunlight-reflecting members create blind spots in the night sky. Light pollution from mega constellations is "a huge problem that needs to be solved," says Federica Spoto, who researches asteroid dynamics at the Harvard-Smithsonian Center for Astrophysics. "And I don't think we're solving it."

Fortunately, an upcoming space telescope, NASA's Near-Earth Object Surveyor, will operate beyond the contaminating reach of the mega constellations. Launching in the next few years—some might say "just in time"—this infrared observatory will peer ahead of and behind Earth's orbit, spying asteroids usually concealed by the sun's glare. If all goes well, it should find 90 percent of near-Earth objects 140 meters across and larger. "Then we can really determine whether we have an imminent threat," Michel says.

And although deflection may be the method of choice for the world's cadre of antiasteroid experts, more nuanced defensive measures are being investigated. "We want more tools in the toolbox," says Rivkin says. "We want not just the hammer but the screwdriver."

Some promising ideas are shockingly simple. The photons within sunlight impart a small amount of momentum on asteroids, ever so slightly altering their orbits. Painting an asteroid white to boost its reflectivity would have the net effect of generating twice the photonic push an all-black asteroid would experience. With enough advance notice, a fresh coat of ivory paint could safely banish an Earth-bound asteroid to the shadowy abyss. Another idea is to park a spacecraft around an asteroid and use its gravity to slowly pull the rock out of Earth's way. But the piloting of a so-called gravity tractor spacecraft would have to be remarkably precise, and it would only work for small asteroids.

CANCELING THE APOCALYPSE

Using a kinetic impactor, for the time being, is the least complicated option available to avert disaster. It is also relatively inexpensive. DART's total budget is about $320 million, "which is not even the cost of a football stadium," Michel says. If DART succeeds in deflecting Dimorphos, then a possible near-term future in which many DART-like missions remain on standby, each ready to launch on one of several readily available commercial spacecraft, is easy to envisage.

But "it's not enough to demonstrate technology," Michel says. The world still needs to set up a system in which the entire planet responds to the threat of an incoming asteroid in as much unison as possible. Which country, or countries, should be involved in the deflection or disruption attempt? At present, although many nations are involved in the search for near-Earth objects and are participating in DART and Hera, America is leading the way on asteroid-deflection technology.

Which countries should aid in any possible impact zone evacuations? When and how should the world decide that trying to deflect or disrupt an asteroid is riskier than simply letting it hit and then assisting the affected nations in their efforts to rebuild? Working groups at the United Nations Office for Outer Space Affairs, as well as biennial tabletop exercises that role-play a potential asteroid impact, are making earnest but so far paltry, efforts at answering these sorts of enormous questions.

Humanity is some way off from having a full-blown asteroid-protection network. But DART's launch is another key milestone in the evolution of planetary defense, once seen as esoteric and perhaps a little silly. "When I was in graduate school in the 1990s, there was a small number of people who were interested, and everyone else treated it as kind of a crank field," Rivkin says.

But so was astrobiology—and now space science is consumed by the interplanetary and even interstellar search for alien life. Thanks to the Chelyabinsk event and other dramatic close encounters with impactors, "planetary defense itself has also undergone a real sea change," Rivkin says. And for what may well be the first time ever in Earth's multibillion-year history, some of its inhabitants could soon no longer be powerless against an insidious cosmic threat.

"This is one natural hazard that we can actually quantify and potentially retire," Bannister says. "That's an amazing goal we can work for. We can't do that with earthquakes. We'll never do that with volcanoes."

Death by asteroid is, by any metric, highly unlikely during any person's lifetime. And yet scientists and engineers want to kill off that threat once and for all simply because they can. "If it's one less thing that anxious people have to worry about when they're trying to sleep, I think that's worth it," Rivkin says. "It's one less piece of existential dread." ■

Avi Loeb is former chair (2011–2020) 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 Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project and is a member of the President's Council of Advisors on Science and Technology. Loeb is the bestselling author of *Extraterrestrial: The First Sign of Intelligent Life beyond Earth* (Houghton Mifflin Harcourt).

Pawel Libera/Getty Images

ASTRONOMY

When Did Life Start in the Universe?

Interstellar xenia, or the welcoming of cosmic strangers, could solve this mystery

Our sun is not a typical star. Most stars are one tenth as massive and will live hundreds of times longer than the sun. Moreover, most stars formed billions of years before the sun, based on the observed star-formation history since the big bang.

Why were we born so late in cosmic history around a relatively massive star like the sun? Statistically speaking, we were more likely to exist earlier or around a lower-mass star.

The Copernican principle asserts that we are not privileged observers of our universe. It stems from the discovery made half a millennium ago by Nicolaus Copernicus that we are not located at the physical center of the cosmos as thought previously. If this mediocrity principle applies to all of our cosmic circumstances, then there must be physical reasons for why our particular form of intelligent life did not arise around an early or dwarf star.

Two obvious explanations come to mind. First, the material that assembled to make early stars lacked the heavy elements that are essential for life as we know it. This includes the heavy elements that make rocky planets like the Earth, as well as the oxygen and carbon needed for water-based organic chemistry. Second, dwarf stars are fainter, bringing their habitable zone closer in. Given this proximity, Earth-like planets would have their atmosphere stripped by stellar winds or their surface sterilized by UV flares from these dwarf stars.

Nevertheless, many sunlike stars with a similar heavy element abundance must have formed long before the sun because we see the products of their death as white dwarfs. It is therefore difficult to imagine that we are the first advanced civilization to appear on the cosmic scene. Can we find evidence for earlier participants in the cosmic story of life?

One approach is to search for signatures of life around older stars in our Milky Way galaxy. The search could target biosignatures, such as oxygen and methane in the atmospheres of planets around them, or technosignatures, such as radio or laser transmission, industrial pollution or city lights.

A second method is to search for early technological civilizations that produced powerful beacons of light or transformed their environment in ways that are detectable across cosmological distances. For the fingerprints to be visible over the vast universe requires them to possess tremendous advances relative to our technological capabilities, as we are still struggling to harvest a tiny

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fraction of the solar power intercepted by Earth.

The third and simplest way is to search within our solar system for technological packages that were shipped to interstellar space by advanced civilizations billions of years ago. The Perseverance rover could bump into the wreckage of such objects on the surface of Mars. We could also search our moon, which serves as a museum for collecting ancient artifacts that crashed into it over time, because it lacks an atmosphere that would burn them up before impact and has no geologic activity that would mix them with its interior after impact.

In total, we should explore early cosmic life in all possible ways to recognize who predated us and what can we learn from them.

Ancient Greek culture during the time of Homer, the reputed author of the *Iliad* and *Odyssey*, valued hospitality to new guests. So much so that the Greek god Zeus was also called Zeus Xenios in his role as a protector of strangers. The concept of xenia reflected the kindness of hospitality.

The ritualized friendship to guests by the ancient Greeks was beneficial because it enabled them to access new information from visitors who arrived at their doorstep from distant territories. Today one might regard this motivation as outdated because of the easy flow of information across Earth through the Internet, global trade and air travel. But the flow of information about life across interstellar space is currently lacking—at least for us. In that context, we should follow the ancient Greeks and endorse xenia with a modern twist.

Interstellar xenia suggests that we should welcome visitors—even if they arrive in the form of old hardware with artificial rather than natural intelligence—which carry information from earlier times. Our technological civilization could benefit greatly from the knowledge it might garner from such encounters. After all, we share the same cosmic neighborhood as these visitors do.

On a recent breezy evening, I noticed an unfamiliar visitor standing in front of my home and asked for his identity. He explained that he used to live in my home half a century ago. I welcomed him to our backyard where he noted that his father buried their cat and placed a tombstone engraved with its name. We went there and found the tombstone.

Our galactic neighborhood could have been visited many times by passing visitors over the past 10 billion years. To find them, we need to monitor the sky and search for unfamiliar objects near our home planet. This is precisely the rationale behind the recently announced Galileo Project, which aims to identify the nature of unusual interstellar objects in the vicinity of Earth.

If we find old visitors, they might provide us with a new perspective about the history of life in our cosmic neighborhood. In so doing, they would bring a deeper meaning to our own life within the keen historic friendship that we owe them in our shared space.

Interstellar xenia might be the key to the prosperity of our culture, just as it led to the intellectual richness of ancient Greek philosophy and literature.

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