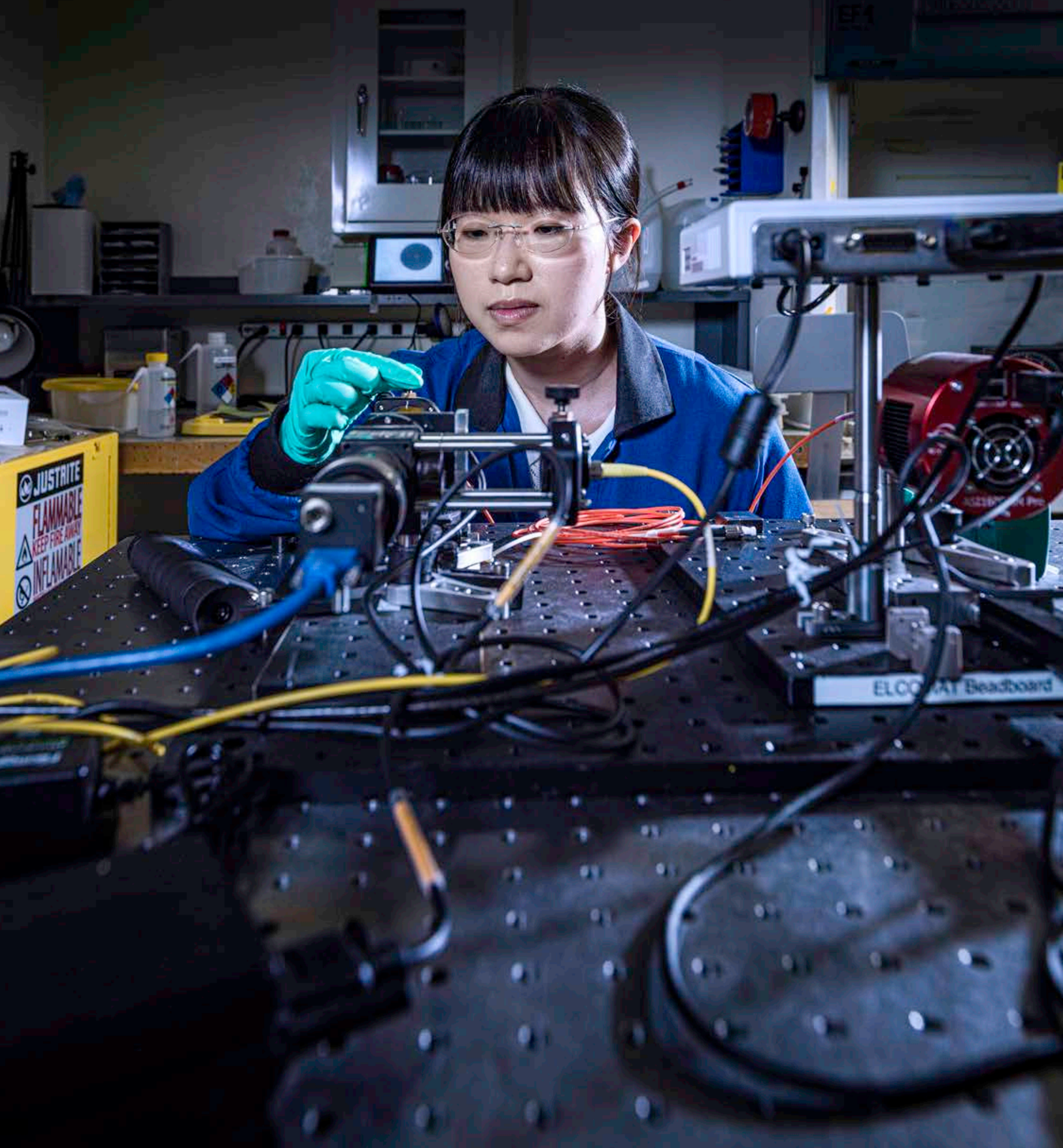
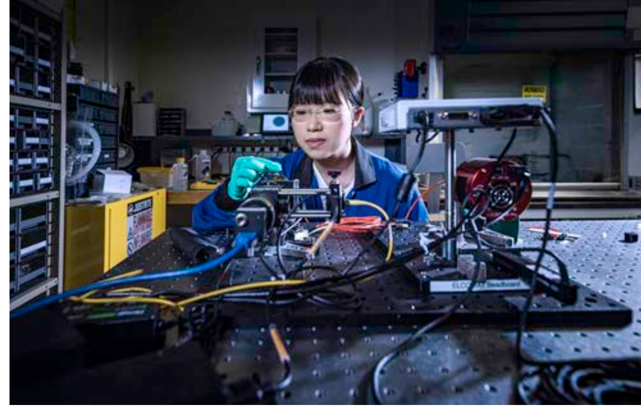
NAUTILUS

CATALYSTS OF DISCOVERY

A special issue exploring bold ideas at Schmidt Sciences



Contents



COVER Sonja Choi uses optical test equipment in a Steward Observatory laboratory to measure the performance of custom fiber optic cables before they are integrated into the Large Fiber Array Spectroscopic Telescope fiber feed. *Photo credit: Chris Gunn/Schmidt Sciences.*

NAUTILUS

Published by:

NAUTILUS Next

CONTACT

360 W 36th Street, 7S
New York, NY 10018

info@nautil.us

SUBSCRIPTIONS

Visit nautil.us/join

Science Is Applied Wonder

BY SWATI PANDEY & CARLIE WIENER

CONSIDER WHAT YOU'RE DOING right now: reading.

It feels simple, even automatic. Yet the act of reading is the product of curiosity, invention, and insight. To truly understand how we read—how photons strike an eye, how signals move through neurons, how perception becomes meaning—is to encounter science in all its interconnected complexity. It takes the tools of physics, biology, neuroscience, computation, linguistics, and more.

That's what makes science profound. It does not live within the boundaries of any single discipline. Wonder does not operate in neat categories, and neither can science. The questions we face—about life, the universe, the fate of our climate, or the capacity of artificial intelligence—are far too large, too layered, to be solved in isolation.

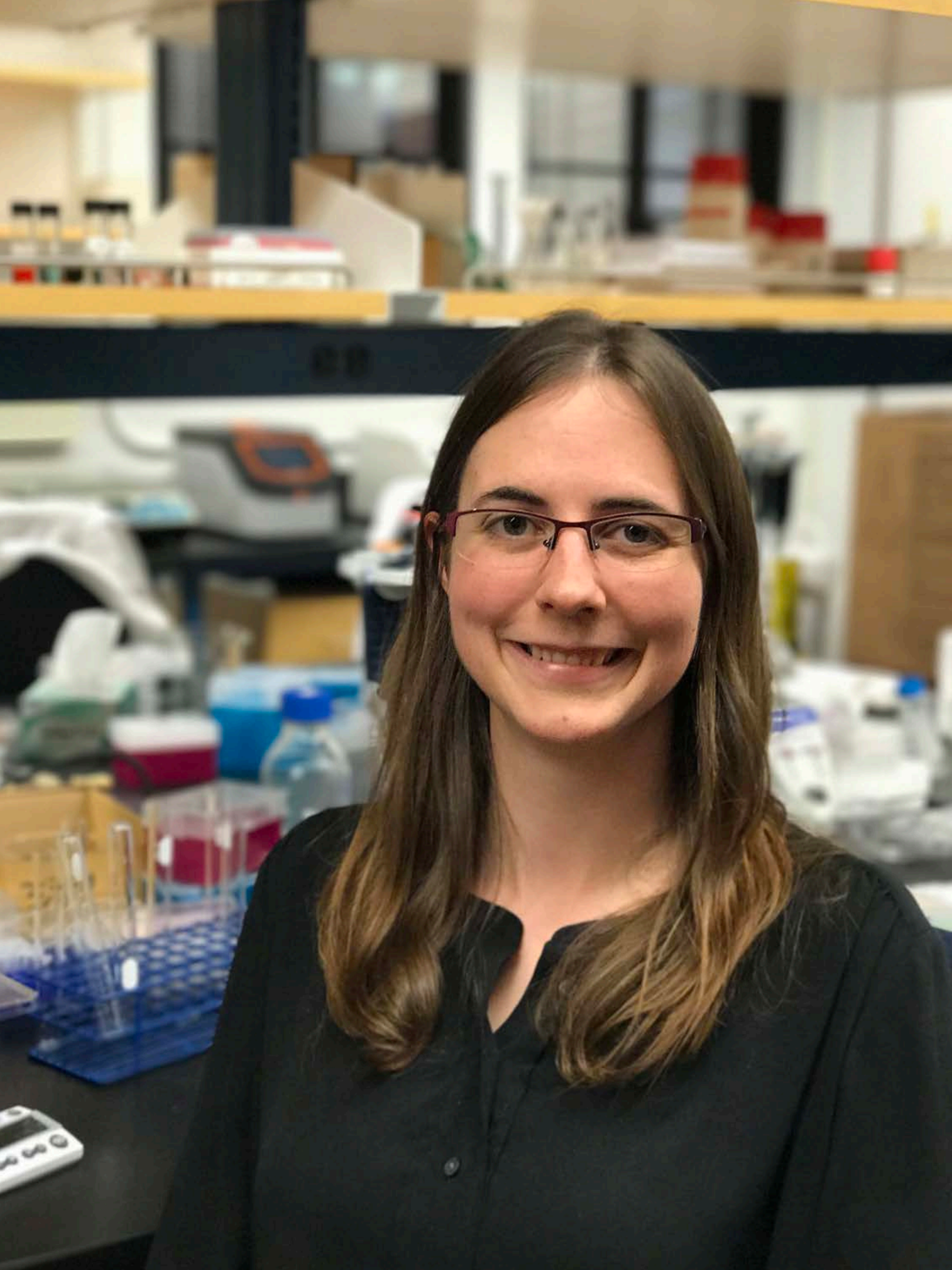
Schmidt Sciences exists to help bridge that wonder into understanding. Founded by Eric and Wendy Schmidt in 2024 with the belief that the most important discoveries often begin as unconventional ideas. "Schmidt Sciences focuses on science-driven opportunities by a broad set of truly remarkable researchers," says Stu Feldman, president of Schmidt Sciences. "We encourage early use of productive technologies and crossing boundaries between disciplines, nations, and scientific cultures."

This means investing in curiosity at scale, prioritizing open sharing and sparking the innovation that thrives when diverse disciplines collide and methods and talents cross-pollinate. Schmidt Sciences cultivates a scientific ecosystem, structured around five areas that reflect the transformative potential of science in the 21st century—artificial intelligence and advanced computing; astrophysics and space; biosciences; climate; and science systems, the infrastructure that underpins discovery.

The thread between wonder and science has not broken.

The scientists and engineers featured in the following pages are following their curiosity to answer essential questions: What's possible? What remains not yet discovered? Some are using machine learning to uncover ancient artifacts; others are planning ambitious space missions, modeling the climate with previously unimaginable precision, or turning seaweed into fossil-free materials. They are connected not by a discipline, but by a shared devotion to the unknown.

Science today faces headwinds: declining public investment, growing mistrust, and a shrinking space for long-term risk. But the thread between wonder and science has not broken. If anything, it's more urgent than ever to weave these threads together into a tapestry that reveals a complete picture. Perhaps redrawing and darkening the line connecting science and wonder could help us remember why science matters, and why we pursue science at all. It's not just vital for discovery. It's vital for our shared future.



The Scientist With an Ever-Expanding Wheelhouse

Ashleigh Theberge is exploring frontiers in chemistry, from the physics of fluid flow to the inner workings of the human body

BY SHAWNA WILLIAMS

ASHLEIGH THEBERGE HAS A LOT of questions. "For as long as I can remember, I've had a strong interest in the natural world and why things are the way they are," says the University of Washington chemist. Among the topics that caught her attention as a child growing up in Maine were mosses and lichens, celestial navigation, geology, and geochemistry. Theberge recalls being excited when she first learned about the scientific method as an elementary school student. "I was quite delighted that this framework existed, and I wanted to be part of folks that used that framework."

Young Ashleigh didn't simply tuck this knowledge away for use in her adult career. Instead, she got to work on experiments—first in her room, then in a dedicated space she and her father constructed above his wood shop. With guidance from high school teachers, Theberge asked whether the herbicide Roundup affected the ability of soil bacteria to convert nitrogen in the air into a form useful to plants, a process known as biological nitrogen fixation. The experiments took years, she says, with methods that progressed from counting bacterial nodules on plant roots to using instruments at the University of Maine to measure the activity of a nitrogen-fixing enzyme in free-living soil bacteria.

COURTESY OF ASHLEIGH THEBERGE

The team devised a device that allows patients to collect their own blood samples at home.

Theberge ultimately determined that Roundup decreased root nodule formation and reduced the activity of the enzyme, suggesting that Roundup may reduce biological nitrogen fixation by bacteria. The project made her a finalist in the prestigious Intel Science Talent Search.

Theberge's unstoppable curiosity continues today as her laboratory at the University of Washington pursues projects ranging from designing at-home biological sample collection kits to exploring the physics of liquid flow to investigating molecules made by filamentous fungi. Her broad-ranging interests made her a fit for the Schmidt Polymaths Program, which supports mid-career scientists pursuing interdisciplinary research.

SCHMIDT POLYMATHS, which Theberge was named a member of last year, suits a researcher who struggled to settle on a single topic to pursue, let alone a single discipline. Theberge says her selection by the Intel talent search led to a summer internship doing small molecule synthesis at pharmaceutical giant Merck, where she was "really thrown into the deep end." She spent another summer at the company's New Jersey headquarters the following year, and a third at a separate Merck site in Pennsylvania after graduating from Williams College in Massachusetts. Theberge still draws on those experiences in industry. "When I'm lecturing quantitative analysis with undergraduates, I talk about calibrating the balance at Merck and how what we're doing is still very relevant to industry work," she explains.

As an undergraduate, Theberge did projects in microbiology, organic synthesis, geochemistry, and paleoclimatology, and spent a summer on inorganic chemistry at Argonne National Laboratory near Chicago and another in a physical chemistry lab at Williams. She says she enjoyed all of those forays into the world of research. Even after settling on a lab for her graduate work—that of Wilhelm Huck, then at the University of Cambridge, where she planned to focus on polymer synthesis—she found herself captivated by a yet another new area after seeing a talk on microfluidics the summer before her senior year. Microfluidics refers to the manipulation of small amounts of fluids through channels less than a millimeter wide. It's applied both in the lab, in tools such as "organ on a chip" devices that replicate aspects of human physiology for study, and in uses such as point-of-care diagnostics.

CLAUDINE GOSSETT

HIGH-TECH LOLLIPOP Theberge and her collaborators developed CandyCollect, a microfluidic device that can capture bacteria in saliva in order to diagnose infectious diseases.

Fortunately, it happened that Huck's lab had just begun its own microfluidics research, and he agreed to Theberge's proposal to do her thesis research in that area. Microfluidics turned out to be a space that's amenable to scientists pursuing diverse interests. "One of the great things about microfluidics that I really like is that it is very interdisciplinary," she notes. "It's a tool that you can bring to bear on many different questions across many different fields."

Indeed, Theberge managed to structure her thesis as a compilation of assorted projects: devising a new catalyst for a type of organic reaction she'd carried out at Merck; a way of both purifying chemicals from a mixture and separating them into droplets of varying concentrations; and the multi-component construction of an organic molecule. This last project included the use of a biological catalyst, or enzyme, which Theberge describes as "kind of dipping my toe into biology" for the first time since her youthful Roundup study.

"For the first time I've needed to buy space on a supercomputer."

Theberge leaned further into biology with her postdoctoral work in David Beebe's lab at the University of Wisconsin-Madison. There, she was part of the biomedical engineering department rather than chemistry, which she found "a little bit disorienting" at first. In Beebe's group, Theberge worked on microfluidic devices that incorporated cells—for example, to replicate disease conditions for study. In a separate project, she worked with Erwin Berthier, a biomedical engineer at the University of Washington, on a two-layer microfluidic device that could separate small molecules synthesized and released by cells to make them easier to analyze.

All told, "by the end of my biomedical engineering postdoc, I felt extremely at home in biomedical engineering," Theberge says. Newly comfortable, she applied for faculty positions in biomedical engineering departments as well as in bioengineering, biophysics, and multiple types of chemistry. "I felt like I could be at home in any of those departments, but it would depend on the department's ability to have an open mindset around interdisciplinary work," she explains. She found that at the University of Washington's chemistry department, and that openness was paired with high-caliber science, collegiality, and a willingness to meet her lab's needs for multiple types of space and equipment for its wide-ranging work. Theberge also has an adjunct appointment in UW's urology department, where she collaborates on studies of urinary tract infections and male infertility.

Theberge co-leads her group, dubbed the Bioanalytical Chemistry for Medicine and the Environment Lab, with Berthier. Asked for specifics on the group's work, Theberge hesitates. "We probably have like, three dozen or so projects," she says, offering to describe a few examples.

IN ONE OF THESE PROJECTS, the team devised an add-on to an existing device that allows patients to collect their own blood samples at home for analysis. The RNA in such a sample would normally degrade quickly, so the researchers developed a tube containing a chemical that stabilizes RNA, a compound found in all cells that helps translate DNA into proteins. RNA can reveal which genes cells are using at a given time, giving a window into the body's inner workings. The lab got so many requests for the stabilizer tubes—from academia, pharma, and government researchers—that they decided to commercialize them, she says. She, Berthier, and another colleague, Sanitta Thongpang, have cofounded a startup company to that end.

Theberge's lab is interested in using the blood collection and RNA stabilization devices to study the health effects of exposure to wildfire smoke by monitoring changes in participants' gene activity over time. In a pilot study, Theberge and her colleagues found that RNA in blood collected and stored in the special tubes maintained its integrity unrefrigerated and exposed to heatwave temperatures. Her lab also had volunteers in western states use the devices to collect blood samples from volunteers when the region was blanketed in wildfire smoke in 2021. Preliminary data from samples analyzed so far indicate that gene activity associated with inflammation changed with wildfire exposure. The researchers are now conducting a similar analysis on more samples from additional subjects collected in 2021 and 2022.

In another application of home blood collection and stabilization, Theberge is working with clinicians at New York University to test patients with either rheumatoid arthritis or psoriatic arthritis as their doctors work to determine which drug will benefit their particular case. "People could sample themselves at home after getting on a new drug, a biologic, for these diseases," she explains."And then be moved to a drug that works better for their disease sooner." The typical process now is for a person to be put on a particular drug, and just give it a go for a few months. Then they would rate their pain on a scale, and maybe get some blood work—but that blood work currently "isn't giving us really specific biomarkers for specific individuals." According to Theberge, this trial-and-error process can be very slow and painful, sometimes leading to irreversible joint damage if patients aren't administered the right drug quickly enough.

Theberge's research on rheumatoid arthritis goes beyond speeding up the matching of patients with effective drugs. "We're very interested in understanding the molecular mechanisms of the disease and how a particular person's molecular pathways prime them to either respond or not respond to a particular drug," she says. Her lab is also interested in the mechanisms of "why one

CLAUDINE GOSSETT

TRANSMISSION TECHNICIAN
Theberge describing the science behind CandyCollect, a device that blends her passions for physics, chemistry, and biology.

“We’re needing to kind of push the boundaries of what’s known in multiple domains.”

person has a particular disease manifestation and somebody else manifests very differently.” Investigating those questions requires designing and coordinating a clinical study and then crunching reams of data on the level of proteins as well as RNA; “For the first time I’ve needed to buy space on a supercomputer,” Theberge remarks. “It’s moved way outside of a traditional chemistry lab.”

In yet another layer to the lab’s work with the RNA stabilizer tube, Theberge collaborates with a theoretician, Jean Berthier (Erwin’s father), on better understanding the physics, math, and chemistry “that governs the flow of fluids in open microfluidic systems and also systems like that tube,” she says. “He and another student in my group have iterated back and forth on pages and pages of equations” to describe why the tube containing the RNA-stabilizer chemical doesn’t spill if knocked over.

All told, “we’re needing to kind of push the boundaries of what’s known in multiple domains, not just like RNA sequencing and analysis and clinical study design, but also even the fundamentals of the fluid,” Theberge adds.

HER PROCLIVITY FOR BUSTING THROUGH disciplinary boundaries makes the Polymaths program a natural fit for Theberge. The award is extremely competitive—candidates must first be nominated by a partner university or someone in Schmidt Sciences’ network, then be invited to apply, then submit a winning application. Of 130 applications reviewed for 2025, just eight were selected, says Molly Coyne, a senior associate at Schmidt Sciences who supports the Polymaths program. Applicants sketch out ideas for what they’d do with up to five years of $500,000 per year in research funding if awarded. But they aren’t bound to pursue—or continue to pursue—those particular projects.

“The Polymaths program is intended to reach people at [the mid-career] stage so that they have that security, but it’s also intended to provide funding for work that might otherwise be a little bit challenging to find funding for because they are moving in a totally new direction,” explains Coyne. “That’s just not something that typical research structures reward often.”

A separate program, Schmidt Science Fellows, supports people earlier in their careers—at the postdoctoral stage—in pursuing interdisciplinary research.

Theberge agrees that the Polymaths award affords scholars remarkable flexibility in the questions they choose to tackle. “It’s almost the fact that there is no requirement [to pursue a specific project] that makes it so amazing, because it allows people to take high risks, to move into new areas, to just completely pivot their research,” she says.

"One of the things that we hear often is that this award allows [recipients] the time, the funding, and the brain space to just get back to more curiosity-led work," Coyne says. "And often that might be why they wanted to be a researcher in the first place."

It's been helpful to bounce ideas off of "like-minded people, people that also are crossing disciplines."

In total, Schmidt Sciences has awarded 35 Polymaths since the program launched in 2021. They meet in-person with each other and with Schmidt Sciences staff once or twice per year. It's been helpful to bounce ideas off of "like-minded people, people that also are crossing disciplines or maybe making pivots and are not just going to be putting in proposals or submitting to journals that are well within their wheelhouse," Theberge says.

With the new Polymath funding, Theberge says her lab is now working with a collaborator to develop a means of stabilizing urine samples for later analysis. In the same vein of at-home blood and urine sample collection, the group is also collaborating with different researchers to collect tiny, information-rich packets called extracellular vesicles from saliva using a lollipop-like microfluidic device. Theberge and her colleagues previously developed the device, dubbed CandyCollect, to nab bacteria from saliva in order to diagnose infectious diseases, such as those that cause sore throat.

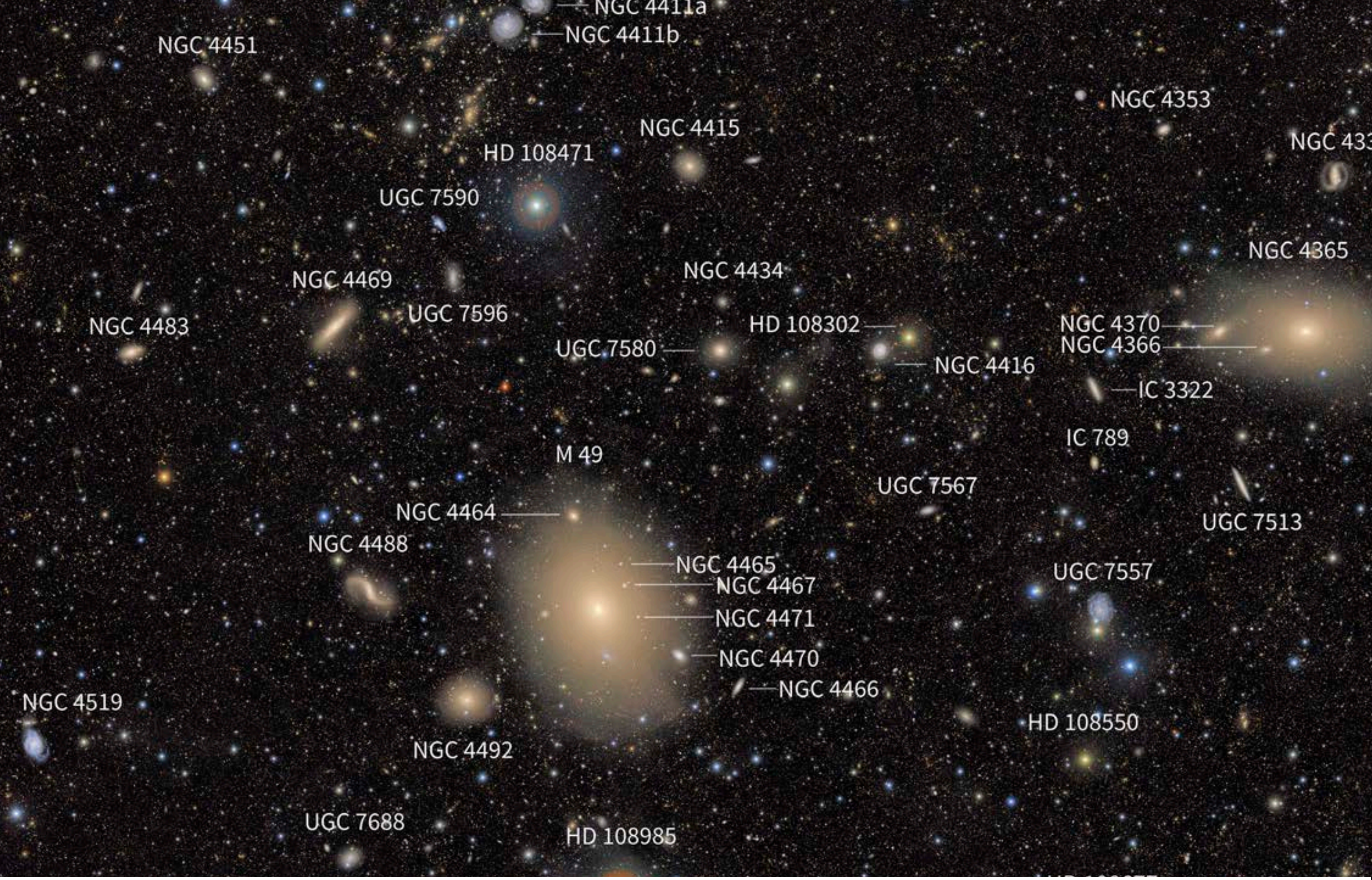
By contrast, extracellular vesicles in the body originate from our own cells. The fat-encased bubbles bud off, carrying with them nucleic acids and proteins that reflect the cell's inner workings. Capturing these vesicles with CandyCollect "positions us to have sort of a window into the cell in other parts of the body that then gets shed into saliva," Theberge says. And the resulting data could ultimately be combined with that from blood tests to reveal a more complete snapshot of a person's health.

Developing tools such as the RNA stabilizer and CandyCollect that others want to use is a rewarding aspect of her group's work, Theberge says. "There is another category of projects that becomes intertwined with the tool development ... which I'll say is our fundamental research" into questions ranging from fluid flow to the mechanisms underlying disease, she observes. "Both are important. They often connect. And I'm really happy that in a given day, I could spend an hour on one and then two hours on the other and then jump back and forth."

Even with her already impressive list of innovations, Theberge says it's not a particular discovery, invention, or award that makes her most grateful. Rather, it's her mentorship—including instances where trainees have made an argument contrary to her own thinking and proven their case. Theberge has thought hard about the way she and Erwin Berthier run the lab, which involves allowing members to make certain decisions autonomously in consultation with others who will be affected.

Mentorship also colors how Theberge sees the potential impact of the Polymaths program on the scientific enterprise. With an eye on more conventional funding mechanisms, well-meaning researchers might advise trainees or other junior colleagues with diverse interests to specialize in order to convincingly demonstrate deep expertise in a given area, she notes. But the Polymaths program is "a paradigm where you can be successful, and you can get funding based on having interdisciplinary interests—and not just interdisciplinary, but projects in vastly different areas," Theberg says. "I think that's really, really helpful and not only to me, but to the whole future of people coming up through the ranks in science."

SHAWNA WILLIAMS is a freelance writer and editor based in Queens, NY. Her work has appeared in publications including *The Scientist*, *BioSpace*, and *Hopkins Medicine*.



NSF–DOE VERA C. RUBIN OBSERVATORY

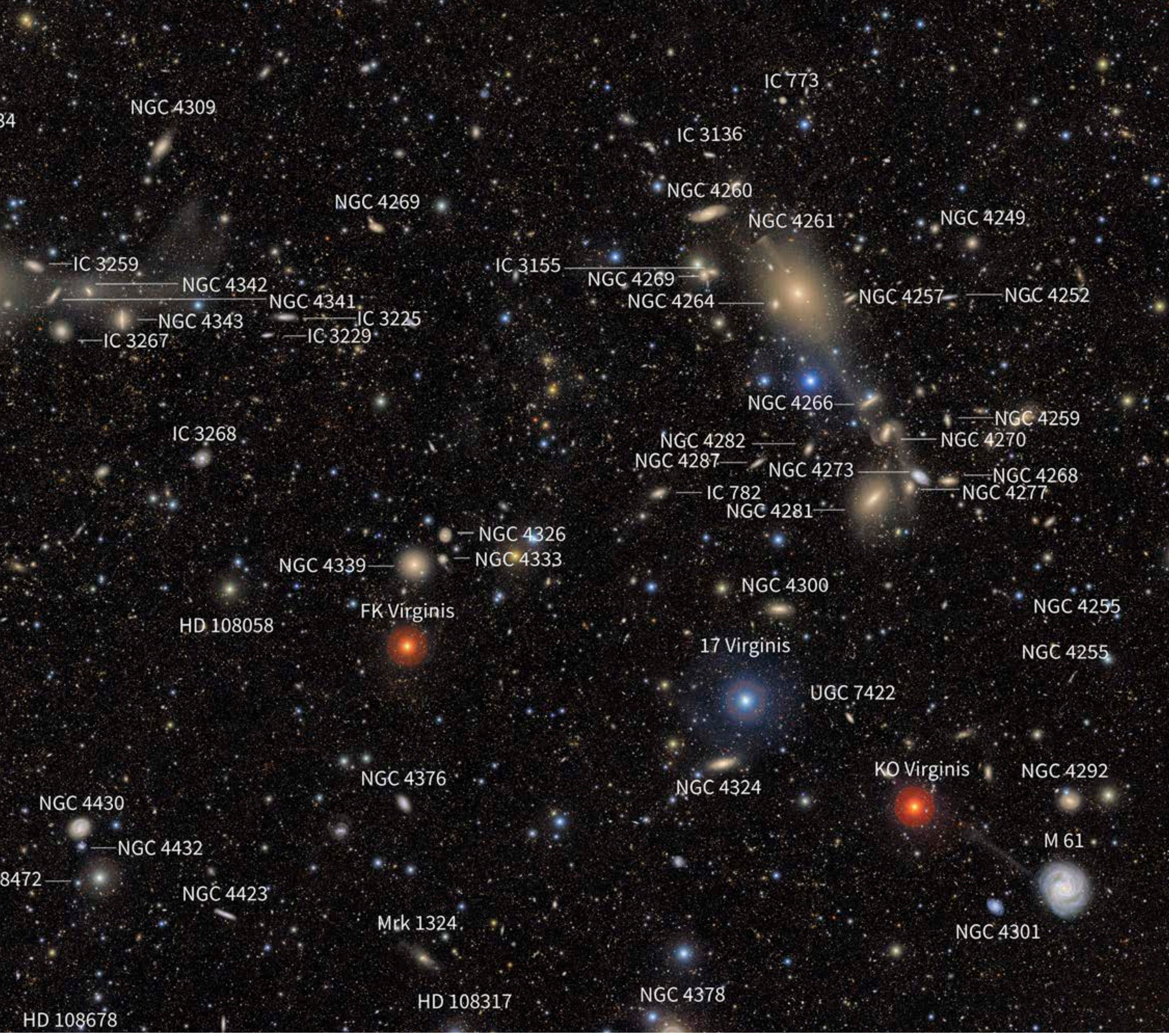
Creating a Cosmic Movie

Making sense of a new era of time-domain astronomy from the Rubin Observatory

BY ELIZABETH FERNANDEZ

O**N JUNE 23, 2025**, the world saw the universe with a new pair of eyes.

That was the release date for the first images from the Vera C. Rubin Observatory. These pictures showed a kaleidoscope of dazzling galaxies, swarms of previously undetected asteroids, and variable stars flashing. The pictures are breathtaking and were compiled after a mere 10 hours of observing. And it's only the beginning.



The Rubin Observatory, nestled high in the mountains of Chile, will not spend its time imaging individual stars, galaxies, or planets, nor does it have a single type of target. Rather, over the course of the next 10 years, Rubin will scan the entire southern sky again and again, creating a time-lapse movie of the cosmos. In addition, certain patches of the sky, called “Deep Drilling Fields,” will be imaged some 23,000 times, giving an even more precise time-varying picture of the sky. It’s the largest movie on the biggest screen, and astronomers can’t wait.

Called the Legacy Survey of Space and Time (LSST), it’s an ambitious project that will enable a plethora of astronomy to be done in various disciplines. Astronomers will be able to detect things that would be impossible to see in a single observation, such as asteroids traveling through the inky blackness of space, supernovae exploding, stars dimming or brightening, or exoplanets orbiting their stars.

"Rubin is expected to detect about a million new supernovae per year."

This cosmic movie will contain a historic amount of data. Rubin will take three images a minute with a 3,200 megapixel camera. This means that every night, Rubin will produce 20 terabytes of data. That's more than 60 petabytes by the end of the survey.

It's a lot of data, the likes of which astronomers haven't dealt with before.

"The amount of data is truly mind-boggling. It's the largest camera ever built for astronomy, and its output of data is a lot to reckon with," says Colin Orion Chandler, a planetary scientist at Northern Arizona University.

"Astronomers have always been so photon starved," says Arpita Roy. "We're about to move into this inverse era, I think that's going to be incredible." Roy leads astrophysics and space at Schmidt Sciences. Existing strategies for data management will be woefully inadequate to deal with the massive amount of data coming out of Rubin. So to help prepare scientists to deal with this amount of data, Schmidt Sciences is providing support for a team of astronomers, data scientists, and software engineers working on a project called LINCC Frameworks. LINCC stands for the LSST Interdisciplinary Network for Collaboration and Computing. A collaboration between the University of Washington, Carnegie Mellon University, and the LSST Discovery Alliance—and supported by Schmidt Sciences—LINCC is a massive initiative to compile ways to handle this raw data from Rubin, processing it quickly and efficiently so that it can be used by astronomers. Various software tools provided by LINCC will help astronomers parse the data, whether they are looking for comets, modeling light curves of supernovae, or mapping dark matter.

MOVING PICTURES This image, from the Vera C. Rubin Observatory, reveals numerous asteroids flying through space (indicated by the colored lines), as well as two distant galaxies from the Virgo Cluster.

NSF–DOE VERA C. RUBIN OBSERVATORY

COSMIC WANDERERS

Remnants from our solar system's formation, more than 1 million known asteroids lurk in our solar system. They are numerous, yet tiny, having cumulatively less mass than the Earth's moon. Because of this, asteroids have always been difficult to spot. However, astronomers have a trick up their sleeves. Time-lapse observations, such as the ones Rubin will provide, create a movie of our solar system, allowing asteroids to quickly stand out as they move swiftly in front of a background of the more stationary stars. This method will also allow scientists to find previously unknown comets—icy snowballs that come from the outer reaches of our solar system.

Rubin's method of searching the sky is already proving incredibly fruitful for finding these cosmic wanderers. Even after the initial 10 hours of observations, it was clear that LSST would find asteroids. A *lot* of asteroids.

A BUSY UNIVERSE Detailed images from Rubin are revealing the distant dynamism of the heavens. This slice of the Virgo Cluster's many galaxies shows two large spiral galaxies as well as three others that are in the process of merging.

"One of the things that was most stunning ... that took me by surprise, was the number of asteroids they got just in a few pointings," says Roy. In the first 10 hours of observations, Rubin found more than 2,000 new asteroids—several of which were beyond Neptune and seven of which were considered "Near-Earth Asteroids" that spend some time in the Earth's neighborhood.

In order to find these small cosmic wanderers, Chandler is developing a LINCC Framework approach called the Kernel-Based Moving Object Detection (KBMOD). KBMOD will help scientists quickly parse Rubin's massive amount of data to find small moving objects such as asteroids and comets.

Chandler points out that, while finding these objects is interesting, there's valuable science to learn as well. These observations may give us hints about how our solar system formed. "I'm very excited by the prospect of finding more comets to improve our understanding of where ices are found in the solar system, and even where Earth's water came from," he says.

Interstellar objects, ones that originate outside of our solar system, have also already been detected. These objects can give us hints about the formation conditions of planetary systems outside of our own.

NSF–DOE VERA C. RUBIN OBSERVATORY

EXPLODING STARS

As Rubin images the sky night after night, it is excellently poised to detect transient phenomena—cosmic events that are here one moment and then gone the next. A prime example is supernovae—exploding stars that are gone in the blink of an eye in cosmic time. To detect these events, it's important that LINCC Frameworks not only work well, but work quickly.

Certain types of supernovae can peak and fade over the course of a hundred days, others a mere month. This might sound like a long time, but astronomers don't have this entire time to observe the supernova. First, the supernova needs to be found, and follow-up observations (sometimes at different wavelengths) need to be made. These are all easiest when the supernova is at its peak brightness and before it fades from view.

Rubin will scan the sky every three to four days. This is enough to image a plethora of exploding supernovae. But actually finding them in the data is another story. "A big question that we've been battling with is, how do you sort through this much data?" says Kaylee de Soto, a LSST-Data Science Fellow at the Center for Astrophysics at Harvard University. "For context, Rubin is expected to detect about a million new supernovae per year, which is far more than anything we've dealt with."

"How do you sort through this much data?"

"I just find that really exciting. I like the idea that we're looking at something that inevitably disappears," says de Soto. "We have a month to learn everything we can about it. And then next month, there will be a whole new set of objects to look at."

Here, machine learning algorithms will come into play, which can automatically filter the data, looking for new bright points of light that herald a supernova. When one is found in the data, an alert will go out in real time. De Soto works to help automate the categorization of these supernovae. She designed Superphot+, a LINCC framework that quickly analyzes the photometry, or brightness, of a supernova. These alerts contain not only a notice that the supernova has occurred, but also labels and categories that help identify prime targets for further research, explains Ashley Villar, an astrophysicist at Harvard University.

GRAPPLING WITH DARK ENERGY

Rubin's data about exploding stars might give astronomers another insight—one into the mysterious force known as dark energy.

Naively, looking out at the cosmos, we expect distant galaxies to be slowing in their expansion—pulled together by the mutual force of gravity. Surprisingly, however, distant galaxies are actually moving faster and faster away from one another—indicating that some unknown force counteracting gravity is pushing galaxies farther apart. The repulsive force of dark energy also slows down the development of cosmic structure. The nature of dark energy is one of astronomy's biggest mysteries.

NSF–DOE VERA C. RUBIN OBSERVATORY

TIME-LAPSE
Because it gathers so many images, the Rubin Observatory can bring to light previously unnoticed detail. This combination image compiles more than 670 images taken over the course of about seven hours. It reveals new subtleties of the Trifid and Lagoon nebulae and their gas clouds, thousands of light-years from us.

A special type of supernova—dubbed supernova type 1a—may help provide clues to dark energy. Because supernovae type 1a have a uniform intrinsic brightness, comparing how bright they appear gives us an excellent estimate of the distance of their host galaxies. As Rubin catalogs more and more supernovae type 1a, we will have a better understanding of how dark energy is affecting the cosmos.

"Those are the two things that we try to measure: the accelerated expansion and the impact of that on cosmic structure," explains Rachel Mandelbaum, a co-PI for LINCC Framework based out of Carnegie Mellon University. By imaging each area in the sky so frequently, more supernovae can be found and followed up on to try to decipher the strange force of dark energy.

NARROWING IN ON THE UNEXPECTED

Having automatic frameworks in place to process and sift through the enormous amounts of data certainly helps certain fields of astronomy where astronomers know what they are looking for. But science really moves forward when we find something completely unexpected. If these data-analysis frameworks are based on known types of objects, such as comets or supernovae, it begs the question—how will astronomers discover something truly new and anomalous?

"Throughout the history of astronomy, discoveries have often been made by someone looking into the data, noticing something weird, and investigating what they saw," says Konstantin Malanchev, a LINCC project

How will astronomers discover something truly new and anomalous?

scientist based out of Carnegie Mellon University. "The problem is that with the current volume of data, human-driven discoveries are becoming really difficult."

Malanchev is a co-convener of the LSST Informatics and Statistics Science Collaboration Anomaly Detection Interest Group. He explains that the amount of data can be a benefit here, as long as one is creative about using it. By filtering out known objects and using techniques such as machine learning, anomalous events or objects can be detected. "My hope is that a combination of machine learning, human expertise, and a bit of luck will lead to new discoveries," he says.

And new science is bound to happen. Andrew Connolly, a co-PI of LINCC Frameworks at the University of Washington, explains. "When you open up a new window on the universe, [in this case] the window of time, you have an opportunity to discover many new phenomena and types of stars and galaxies—new astronomical sources or events that might test our understanding of how the universe formed and evolved."

"The challenges are the sheer data volume," says Anais Möller, a physicist at Swinburne University, who isn't involved in the LINCC work. "Meeting this challenge means embracing big data technologies like distributed computing [and] machine learning, because at this frontier, frontline discoveries are inseparable from frontline technology."

The amount of insight promised by the Rubin Observatory will be a treasure trove for scientists for decades to come—but only in as much as the massive amounts of data can be processed and put to good use.

ELIZABETH FERNANDEZ is a freelance science writer who covers astronomy, physics, geology, and the hard sciences, as well as science and society. She can be found at sparkdialog.com.

How “Plant Math” Can Help Predict the Climate’s Future

Researchers are building equations for vegetation processes that might improve climate models

BY ULA CHROBAK

THE EARLIEST CLIMATE MODELS of the 1960s and '70s had a bare land surface with no plants. In these models, rain would fall into mathematical "buckets," then evaporate back into the air, to simulate the water cycle.

Since then, climate models have come a long way in representing forests, grasslands, and other biomes and how they influence the Earth's water and carbon cycles. But you still might call them a little low-fi. The global climate models of today tend to have only about 10 "functional types" of plants, which approximate how different ecosystems move heat, water, and nutrients—including carbon.

And these plant simulations don't exactly replicate how responsive flora are to shifts in their environment. That's because when these models were built, they assumed a stable climate. Now that plants are adapting their photosynthesis to warmer temperatures and increased carbon dioxide, they need new math to represent them in climate models. So one team of researchers created the LEMONTREE project, which is building equations that describe "plant math": how vegetation optimizes its functions, given a set of climatic variables. (LEMONTREE is short for Land Ecosystem Models based On New Theory, obseRvations, and ExperimEnts.)

The team consists of researchers from around the globe with support from Schmidt Sciences Virtual Earth System Research Institute (VESRI). Their expertise also roams widely, from plant ecology to math to remote sensing. "The idea is that we can simplify the models that we use to predict how plants react to climate and how they're going to react in the future, and also how they will then influence the climate," says the project's lead researcher Sandy Harrison, a professor of paleoclimates and biogeochemical cycles at the University of Reading in England.

Even as global climate models have grown more complex and powerful, plant processes are still their weak spot, says Harrison. For instance, in the Intergovernmental Panel on Climate Change's reports on climate change, one major area of uncertainty is how vegetation will respond to warmer temperatures and increased carbon dioxide. In some model outputs, plants continue absorbing carbon for many decades into the future, in turn somewhat buffering human emissions. In other models, plants wither in warmer weather, even becoming a net source of CO_2 by 2050.

PAGES 24-25: GEORGE TRUMPETER / SHUTTERSTOCK

Will plant life on Earth thrive with some extra CO_2?

While physicists have built equations that elegantly describe the atmosphere, ocean, and physical landforms, terrestrial life and especially plants present a unique challenge. Unlike physical forces, plants adapt and evolve. Species adjust their growing strategy to make smart use of water, sunlight, and nutrients. That's why the amount of carbon that plants take up every year varies—while, on average, it's about a third of all the CO_2 emitted, there are stark differences year-to-year as plants respond to the environment.

However, climate models typically include rigid parameters for plant functions. For example, they might prescribe that a pine tree always photosynthesizes most efficiently at 77 degrees Fahrenheit. But these values miss how much plants can flex their functions. "They don't change during the seasonal cycle or droughts," says Harrison of hypothetical plants in climate models. "That means that the plants are less responsive to these climatic events than they ought to be."

For example, a study last year found that many current climate models underestimate how sensitive plants are to drought. Researchers used satellite data to study how canopies responded during dry periods, and compared this response to existing climate models. The researchers found that vegetation reduced photosynthesis during droughts more strongly than the models predicted.

Small miscalculations like this can add up, leading to misrepresentations of carbon uptake, water evaporation, and more. "Oftentimes, these models were developed using data when maybe it was beautiful and sunny out," says lead author Julia Green, an environmental science professor at the University of Arizona, who is not currently part of the LEMONTREE team but has previously

PRENTICE LAB

SPEAKING IN PLANT Better understanding the nuances of how plants change their inputs and outputs in response to changes in their environment is helping researchers like Colin Prentice, a LEMONTREE lead researcher and a professor at Imperial College London, better calculate their impact in climate models.

For now, plants are slightly increasing their ability to capture carbon.

had research funded by the project. "During extreme conditions, they end up not performing so well."

The LEMONTREE team wants to solve this problem by rebuilding plant models from the ground up. In particular, they are guided by a theory called "eco-evolutionary optimality."

"It's the idea that through evolution, through ecological processes, plants grow where they're best adapted to grow," said Harrison. To create new models based on this theory, "we simply have to look for the trade-offs that a plant is making."

Photosynthesis is one area where plants make these trade-offs. Plants must open their stomata to pull in carbon dioxide to make sugar, but leaving those leaf pores open too long in dry weather can wilt vegetation. If plants risk it and leave their stomata open too long, they will dry out and die. But overly conservative vegetation will be out-competed by plants that take in more carbon and grow faster. Over time, the organisms that find the perfect balance will win out.

With this balance in mind, the researchers developed an equation that conveys the trade off between stomatal conductance and photosynthesis. They drafted this equation using remote-sensing data that reported canopy greenness. Then, they tested the equation using CO_2 measurements taken at field sites. Through comparisons with field site data, they could test whether the model could correctly predict photosynthetic capacity.

After some adjustments based on comparisons with the observations, the researchers say this single equation for photosynthesis does the work of several more complicated equations in land surface models. "We end up with a model that we can show is substantially more accurate than conventional models, and yet it's a great deal simpler," says Colin Prentice, a LEMONTREE lead researcher and a professor at Imperial College London.

The team is also working on other plant-related math equations, such as ones that determine leaf area and the rate of plant respiration across different environments. Instead of relying on pre-defined plant parameters, the equations work out the best "plant math" for a given location, showing how plants are optimizing their growing strategies based on climate. This allows climate modelers to have more flexible—and therefore hopefully more accurate—projections, says Pier Luigi Vidale, a climate scientist with the University of Reading who is on the LEMONTREE team. "We would like to do away with all these parameters that describe what vegetation does, and try to compute those things dynamically."

An improved mathematical representation of plants in climate models can help answer long-standing questions for ecologists. Importantly: Will plant life on Earth thrive with some extra CO_2, or will drier conditions cause vegetation to desiccate? With more CO_2 in the air, plants can produce the same amount of food while keeping their stomata open for a shorter period, an effect known as CO_2 fertilization. But this benefit extends only as far as plants can have enough moisture and nutrients. With improved vegetation models, "we're able to look at what's going to happen when we have both warming and increasing CO_2," says Harrison.

She says that the new models suggest the effect of recent increases in atmospheric carbon dioxide is fertilization—global vegetation as a whole is greening, which means that, for now, plants are slightly increasing their ability to capture carbon (though not nearly enough to offset ever-increasing human emissions).

But extreme conditions can shift this balance, something LEMONTREE researchers hope their models will better predict. If a drought leads plants to shut their stomata, then they won't release as much water into the atmosphere, which reduces the moisture going to clouds and rainfall, which in turn could lead to even drier conditions. To predict dramatic feedback effects like this, researchers need to capture the relationship between moisture levels and water conductance in plants. "If we manage to be able to predict the vegetation properly, then we're going to get better predictions of what the climate might look like," said Harrison.

Once the equations are finalized, the next step will be seeing how they hold up in larger climate models.

RE-CYCLING Old climate models struggled to capture the complexity of plants' dynamic roles in water and carbon cycles of the planet. A new generation of modeling is working to recalibrate based on real data and better math.

LINOJOCARU / SHUTTERSTOCK

Researchers can then see how the outputs perform compared to previous models of terrestrial ecosystems. After the LEMONTREE project wraps up in June 2027, scientists with CONCERTO (which stands for (improved CarbOn cycle represeNtation through multi-sCale models and Earth obseRvation for Terrestrial ecOsystems), a climate modeling effort funded by the European Union, will collaborate with the team on the next steps toward seeing how the atmosphere and land surface interact in simulations that include the new plant math.

"It's a very helpful way of structuring your model," says Anna Harper, a professor of geography and atmospheric sciences at the University of Georgia, of the team's eco-evolutionary optimality approach. Especially since models are still relatively uncertain about terrestrial processes, any improvements are welcome, adds Harper, who is not involved in the LEMONTREE project. "There's a lot of excitement around anything that can help us better represent the carbon cycle."

That said, rebooting models with a new set of equations for plants is not straightforward. Today's climate models are the result of years and years of tuning, where scientists adjust variables when the model output doesn't line up with observational data. After tuning, the simulations might get the right answer—but for the wrong reasons. So even if the new plant math is more accurate, it might throw off other calculations in the model. "It will just take time, because even if people agree that improvements have been made, you still have to check that it's not going to have unintended consequences," says Harper.

While the changes may be messy, the team thinks it will be worth it in the long run. The climate models developed decades ago and are in need of a refresh, says Vidale. "We still really need to develop models and to take big risks, like we're doing here," he says. "In the end, even if it's a huge failure, it was still worth doing it. But the indication so far is that it's working."

ULA CHROBAK is a freelance science writer based in Nevada. You can read more of her work at ulachrobak.com.

New Life for Rotting Seaweed

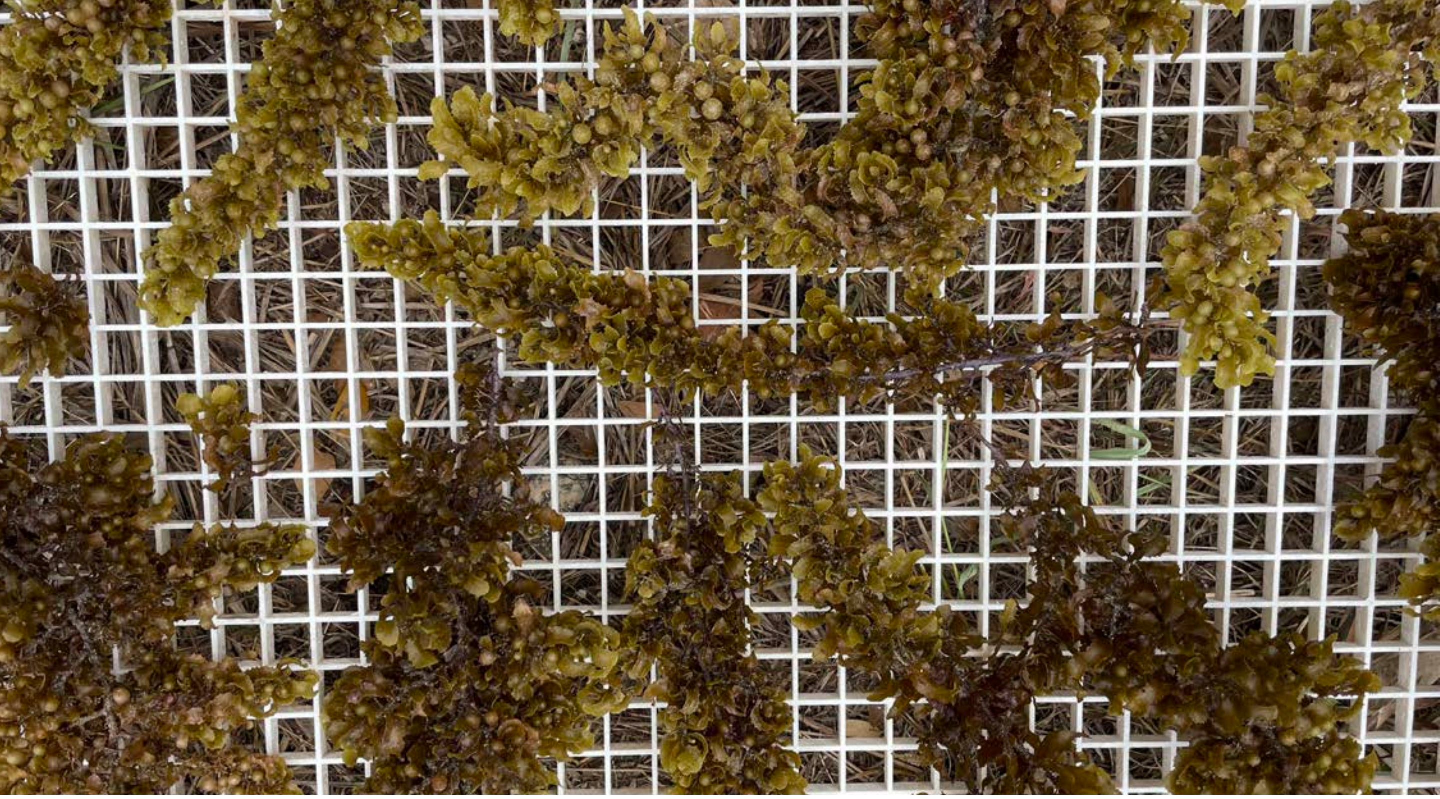
Problematic piles of Sargassum *could serve as useful raw material for a variety of products*

BY LISA S. GARDINER

EACH TIME LORETTA ROBERSON finds herself in an ominous shadow while scuba diving off the coast of Puerto Rico, she discovers that the culprit is *Sargassum*—large mats of golden-brown seaweed floating overhead.

Roberson, a scientist at the Marine Biological Laboratory in Woods Hole, Massachusetts, has led a team to develop a seaweed farm in Puerto Rico for several years. But unlike the varieties grown at the farm, and unlike most seaweeds, the genus *Sargassum* includes species that spend their entire lives floating in the ocean waves. Air-filled bladders the size of small peas called pneumatocysts buoy the algae up to the sea surface where its ochre fronds aggregate to form enormous rafts.

For more than a decade, the amount of *Sargassum* has exploded in tropical Atlantic and Caribbean waters. "There's always been *Sargassum* in the Caribbean, but not at the levels that we're seeing now," says Roberson. Each year massive tangles of the seaweed grow in the open ocean and then wash ashore in mountainous drifts, befouling toney resorts and nature reserves alike. The largest seaweed blooms have contributed to steep declines in visits to once-idyllic tropical beach destinations—one study reported a 9 percent drop in tourism across the Caribbean due to *Sargassum* in 2011.



TRASH TO TREASURE *Sargassum* fronds, like these drying in Puerto Rico, could become the raw material for a host of products, from biofuels to fertilizers.

PAGES 30-31: ARKADIJ SCHELL / SHUTTERSTOCK. PAGE 32: LORETTA ROBERSON

As it decays, the seaweed doesn't just vex sunbathers; it also kills marine life. As a short-term measure in some places, bulldozers and dump trucks remove rotting piles of the beached macroalgae, with most of the mess winding up in landfills. But Roberson is applying her knowledge of seaweed to find uses for this overabundance of *Sargassum*. She is working with Shishir Chundawat of Rutgers University and José Avalos of Princeton University to lead a multidisciplinary network of collaborators from eight research institutions and one company that is exploring how to transform the glut of *Sargassum* into products, finding economic value in the problematic seaweed.

Their project, the Sargassum Biorefinery, or SaBRe, is part of the Schmidt Sciences Virtual Institute on Feedstocks of the Future (VIFF). A biorefinery transforms raw materials into products just as an oil refinery does, but it uses biomass—in this case *Sargassum*—as the raw material instead of petroleum. The institute's five projects aim to make it more cost-effective to use organic matter currently regarded as waste, says Genevieve Croft, Schmidt Sciences senior program scientist. "We have all this biomass lying around that is not only not being used, but could be an environmental harm if we're not using it," she says. "Each of these projects is tackling an economic opportunity, but also potentially an environmental challenge."

The gravity of the environmental challenge posed by Sargassum is what motivates Avalos. "People are suffering economically, and ecosystems are getting ruined," he says. "It's a growing crisis."

***SARGASSUM* IS NATURALLY FOUND** in the center of the North Atlantic, an area known as the Sargasso Sea, which is defined by swirling ocean currents.

"It is a beautiful seaweed, and it has its own unique, essential habitat for organisms," says Roberson. *Sargassum* is nursery and hunting ground for hundreds of species of fish and invertebrates as well as sharks, rays, dolphins, and eels. Young sea turtles rest on the mats, and find food and shelter amid the seaweed blades. Ten animal species live exclusively in this floating *Sargassum* ecosystem.

But, for the past decade and a half, *Sargassum* has been proliferating far beyond the Sargasso Sea, covering a wide swath of ocean now called the Great Atlantic Sargassum Belt, which extends in a band across about 5,500 miles of the Atlantic Ocean—from West Africa to the Caribbean Sea to the Gulf of Mexico.

While the amount of floating seaweed in the belt waxes and wanes with the seasons, its peak amounts have grown over the years. According to satellite measurements analyzed by researchers at the University of South Florida, there was more than 9 million tons of *Sargassum* in 2015, more than 20 million tons in 2018, and over 24 million tons in 2022. Estimates indicate that 2025 will be another record year: In May there were nearly 38 million tons of the seaweed floating in the Great Atlantic Sargassum Belt, according to an update from the researchers.

As it decays, the seaweed doesn't just vex sunbathers; it also kills marine life.

Large volumes of the squishy brown seaweed are pushed into coastal waters and onto beaches by waves, currents, and winds. On beaches, dead *Sargassum* covers sand in a wide ribbon parallel to shore or forms hillocks several feet tall. As it decays, the seaweed releases rotten-egg smelling hydrogen sulfide and ammonia, toxic gases that can cause human health problems including nausea and breathing difficulties.

Sargassum drifts piled on beaches can reduce the availability of sea turtle nesting sites, and can make the already perilous journey from nest to waves even harder to navigate for emerging hatchlings. Where decaying *Sargassum* floats offshore, the mats can block turtles from surfacing for a breath of air and prevent sunlight from getting to corals, seagrass, and other marine life below. Massive influxes of rotting *Sargassum* infuse water with excess nutrients and deplete oxygen, killing fish, crabs, urchins, and mangrove trees.

LORETTA ROBERSON

POSTCARDS FROM THE SEA

Seaweeds, which are actually algae, not plants, can be pressed and dried, like these specimens, which were made by kids during a public outreach event, the Woods Hole Science Stroll. The green leaves are *Ulva*, also called "sea lettuce," the red ones are *Palmaria*, and the brown one at the bottom is *Sargassum*.

BUCKET SCIENCE A Falmouth High School student collects *Sargassum* samples in Woods Hole, MA, in front of the Marine Biological Laboratory with the Woods Hole Oceanographic Institute dock and ship in the background.

Coastal communities in Mexico, including in the state of Quintana Roo on the Yucatán Peninsula, have been grappling with the problems of excess *Sargassum* for years. In 2022, Judith Rosellón Druker, a research scientist with the Mexican government, interviewed Quintana Roo residents about how *Sargassum* has affected their coast. They described a crisis. "Some people were telling me, I cannot go to the beach and enjoy it anymore because it smells horrible and the landscape is depressing," she says. As one resident she interviewed put it, "Everything dies along the coast."

The locals she interviewed also described the economic effects of the environmental changes. While some described new job opportunities with companies managing the *Sargassum*, many more reported a loss in income from fishing and businesses linked to Quintana Roo's tourist epicenters, such as Cancun and Playa del Carmen. A 2022 study led by the Inter-American Development Bank estimated that economic activity drops nearly 12 percent when Quintana Roo coasts are swamped by *Sargassum*.

So *Sargassum* represents a double-edged sword. Swirling in the Sargasso Sea at a population right-sized for the environment, *Sargassum* creates crucial habitat. But once *Sargassum* is headed for a coast, "you cannot consider that an ecosystem that should be protected," Rosellón Druker says.

While there is still more to learn about why *Sargassum* is proliferating so rapidly, a key cause is likely the dramatic increase in nutrients, including nitrogen from fertilizers, carried into the ocean by runoff. It's also possible that nutrients are arriving with dust blown off the Sahara Desert, which settles into the Atlantic. The amount of such windblown dust is increasing as the climate changes and the Sahara grows drier.

LORETTA ROBERSON

There was more than 9 million tons of *Sargassum* in 2015 and over 24 million tons in 2022.

The warming temperatures and abundant sunlight in the tropics also help the seaweed grow more quickly. A study published in 2023 reviewed the effect of projected climate warming on *Sargassum* and found that by 2050 it's likely that the blooms will last for more of the year and happen at higher latitudes. If ocean waters get too warm, vast rafts of seaweed may die during the hottest months. While predicting long-term, future ecological events in rapidly changing oceans is uncertain, it's possible that the Sargasso Sea's population of *Sargassum* may multiply in warming waters, sending rafts of seaweed to mid-latitude beaches along the United States East Coast.

MOST OF THE *SARGASSUM* gathered from beaches is destined for landfills, but as uses for the seaweed as a feedstock—or raw material—are emerging, new companies are popping up across the Caribbean to take advantage.

While making use of *Sargassum* is relatively new, other types of seaweed have been used for thousands of years for food and more recently to make chemicals to stimulate plant growth, bioplastics, and renewable energy. Converting seaweed to energy has a much smaller environmental footprint than traditional oil and gas production, says Michael Huesemann, an engineer at Pacific Northwest National Laboratory who studies methods to develop biofuels, vegan protein for foods, and other products from seaweed. Unlike other sources of biomass, seaweed doesn't require freshwater or land, he adds. Huesemann has not yet worked with *Sargassum* but can see the appeal because its blooms mean there is no need to farm it, as is typical for other seaweeds used in industry.

Using *Sargassum* to produce biofuels is of keen interest to Caribbean nations, such as Barbados, that are transitioning to renewable energy. In 2019, Legena Henry, a mechanical engineer and University of the West Indies lecturer, and her undergraduate students were searching for ways to make biofuels locally. Experimenting, they discovered that useful quantities of biogas could be produced from a combination of rum distillery wastewater and *Sargassum*.

With Henry as the CEO, Rum and Sargassum, Inc. spun off from the university and today is operating a large biodigester—a tank that uses microbes to break down organic compounds in *Sargassum* and wastewater into biogas. With conversion kits installed, four cars are now running on biogas instead of gasoline.

The project plans to eventually convert 120 conventional taxis serving Barbadians to run on this *Sargassum*-based fuel. Initially, Rum and Sargassum will sell compressed natural gas to the taxis. After two years, the profits will be used to build a 250-killowatt biogas plant. "The taxis will not even know when they switch over to renewable biogas, except their costs will go down," says Henry. She hopes investors will help Rum and Sargassum increase the scale of biogas production and estimates that 32 similar biogas plants would be needed to rid Barbados beaches entirely of *Sargassum*.

BUILDING ON EXISTING USES for seaweed, the Sargassum Biorefinery team is one year into a five-year search for new ways to turn *Sargassum* into a bevy of products.

"The impact of the project transcends national boundaries," says Chundawat. Solutions developed could be implemented in all locations currently

THE (UN)WELCOME MAT
Floating rafts of *Sargassum* form crucial habitat for a variety of ocean creatures. But overproduction of the brown algae causes problems at sea and ashore.

ANDRIY NEKRASOV / SHUTTERSTOCK

vulnerable to *Sargassum*, he adds, which include more than 40 Caribbean and West African countries and territories.

What will they make from the seaweed? It may become biofuels, animal feeds, chemicals to replace petrochemicals, bioplastics, and pharmaceuticals, says Avalos. "But we haven't committed to any specific products," he adds. Discovering more about *Sargassum* and how to break it down into its component parts will help answer that question, says Chundawat.

Before new uses for *Sargassum* are found, there is more to learn about the seaweed's basic biology and ecology. So last fall, Roberson and her team collected samples of *Sargassum* from the water and beaches of Puerto Rico and sent them to project partners.

With her colleagues, Roberson is exploring the biology and growth rates of the three main types of *Sargassum* found in blooms—*S. fluitans* and two varieties of *S. natans*. If they have distinct compositions, each type may be useful in different products.

One challenge posed by turning *Sargassum* into a feedstock is that, as it lives and floats in the ocean, seaweed absorbs toxic heavy metals, including arsenic. This can be beneficial as seaweed can be used to remove toxics from water, but hazardous in products made from the seaweed. "You can't just feed it to animals," says Chundawat, explaining that the project might need to strip toxic compounds out before *Sargassum* is utilized.

But *Sargassum*'s ability to concentrate elements from seawater may have a distinct upside if it also holds onto rare earth elements—valuable metals used in technologies such as phones, computers, electric and hybrid vehicles, and televisions. Small amounts of these elements are naturally found in seawater and accumulate in seaweeds, although it is currently unknown how much builds up in *Sargassum*.

"When you grow seaweed in [seawater], certain rare earth elements … get bioconcentrated in the seaweed by a factor of 10,000 to a million, depending on the seaweed, and depending on the elements," says Huesemann. While the elements concentrate in seaweed, Huesemann cautions that the quantities found so far are too small to be economically valuable. Engineers from UCLA and Roberson are working together to learn how *Sargassum* takes up rare earth elements and how best to extract them.

WHILE ROBERSON FOCUSES on the biology of *Sargassum*, other researchers are focused on its microbiome, including yeast and bacteria that help break down the seaweed. Microbes, like those used in Henry's biodigester, release enzymes that break complex compounds into simple ones. Those simple compounds become the building blocks for products produced in biorefineries.

Sargassum represents a double-edged sword.

Analyzing microbes on *Sargassum* collected from Caribbean beaches, Chundawat and his colleagues are discovering which wild microbes and enzymes naturally break *Sargassum* apart. Rutgers University biologist Debashish Bhattacharya and colleagues are working to sequence the genomes of such microbes. "We're getting insight into the actual genes that are involved in the breakdown of *Sargassum*," says Chundawat.

However, brown seaweeds like *Sargassum* are often harder to break down than other seaweeds. To speed up the process in biorefineries, the researchers plan to engineer super-efficient enzymes and microbes. After finding enzymes that break down *Sargassum* in the wild, they will engineer versions that break down the seaweed more effectively—a type of directed evolution guided by computational modeling. Avalos will then develop microbes that secrete the improved enzymes.

Many of the microbes of interest are bacteria, but Avalos is focused on yeasts that can digest *Sargassum* and live in saltwater. Yeasts have advantages, he says. They can be engineered to produce enzymes and proteins that are harder for bacteria to produce, and they don't seem to get infected by viruses, Avalos explains.

Once there are enzymes that efficiently break down the seaweed, the team will explore what products can be made from the resulting compounds and whether other microbes and physical conditions, such as high pressures and temperatures, can further transform those compounds into useful products.

DESPITE THE PROJECT NAME, the Sargassum Biorefinery does not plan to build an actual biorefinery. Rather, the project aims to develop processes and technologies to convert *Sargassum* into products, paving the way for future biorefineries.

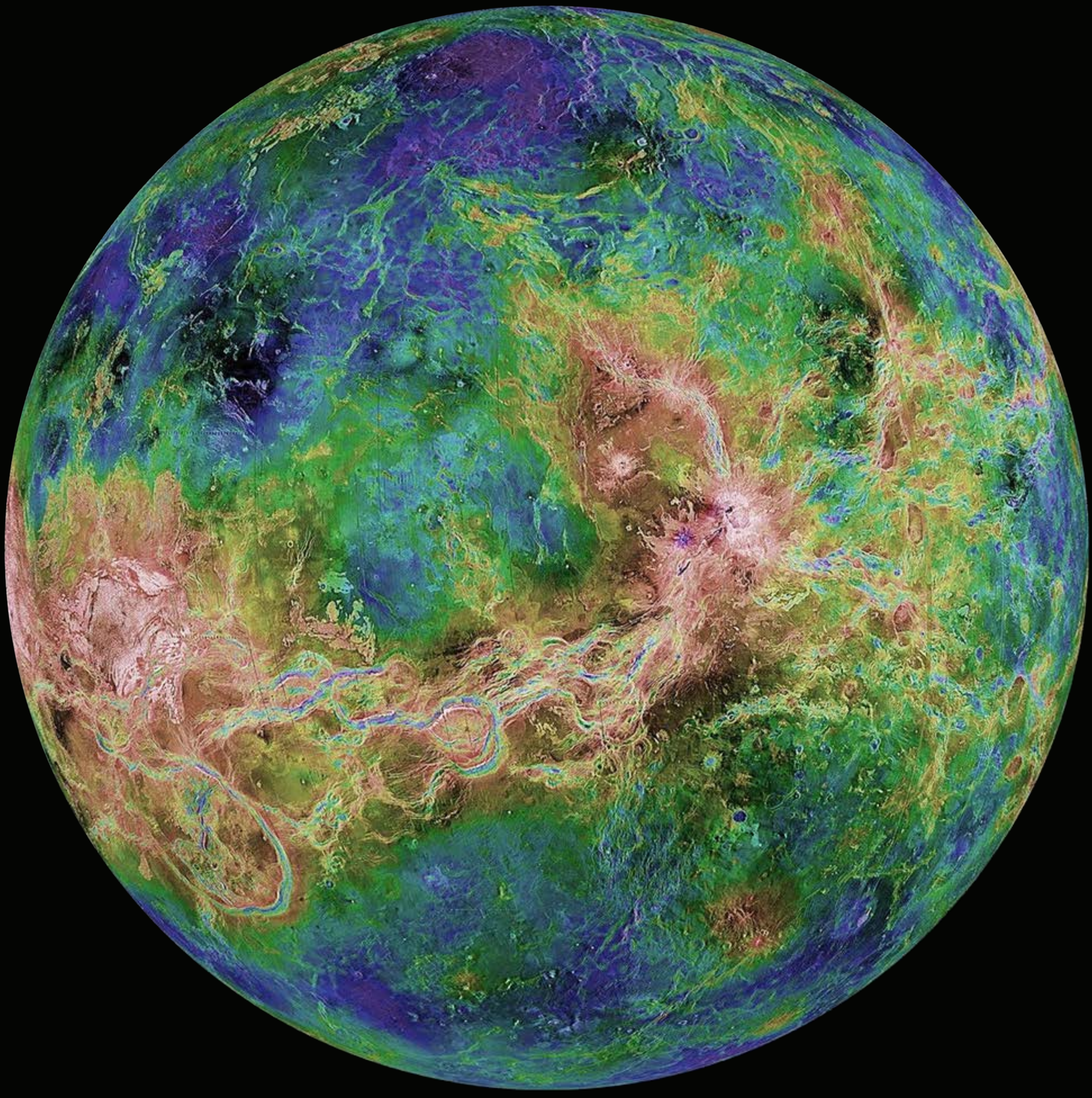
"A dream that we always talk about within the SaBRe team is having a floating biorefinery," says Roberson. If vessels collecting the *Sargassum* also had the technology to process it, products could be made right on the boat. "So while we're collecting, you know, pass it straight into the feed of the biodigester," she says.

Whether or not floating biorefineries become a reality, gathering *Sargassum* while it is still at sea could prevent massive piles of it on beaches and in coastal waters. So Roberson and her colleagues are developing methods to skim the seaweed from the sea surface and haul it onto vessels. Other technology may someday help gather the seaweed too, like electric self-driving tugboats that can tow heavy bags of seaweed to biorefineries onshore, says Roberson. *Sargassum* forecasts are becoming detailed enough to track where rafts of seaweed are floating so that boats know where to collect them.

But what will happen if *Sargassum* overproduction stops after the infrastructure for biorefineries is built? "Maybe we'll one day have a time where we could control the amount of nutrients that are being dumped into the ocean and not have these large blooms," says Roberson. *Sargassum* farms in the ocean could keep the industry going, she says.

"I think the *Sargassum* project is not only addressing the problem of the now," says Chundawat. "It could also be looking at creating opportunities in the future when you could develop seaweed farming technologies in the years to come."

LISA S. GARDINER is a science writer, educator, scientist, and speaker. Her work has appeared in *Yale Environment 360*, *Audubon*, *The Guardian*, *Hakai Magazine*, and elsewhere.



Seeking Signs of Life on Venus

The first private mission to the morning star will explore the planet's clouds

BY LEONARD DAVID

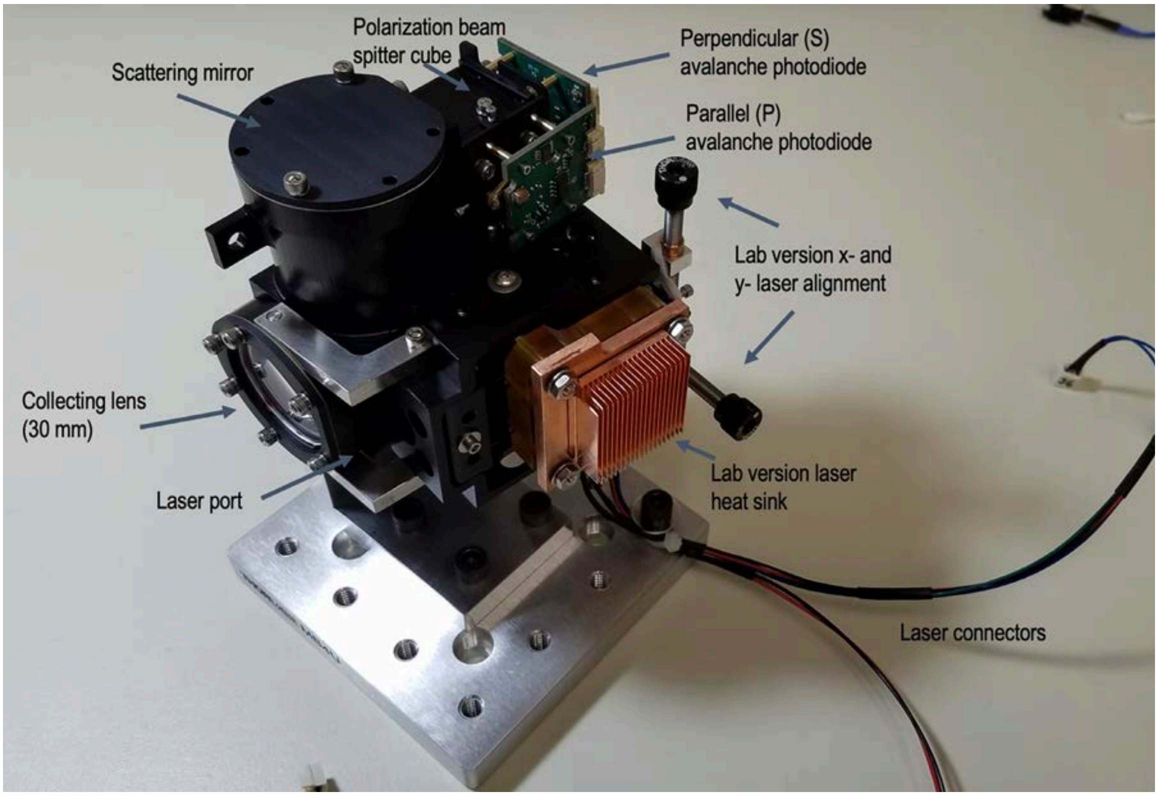
THE PLANET VENUS is a hellish world. Not only is this enigmatic, boiling globe holding tight to its secrets under thick clouds saturated with sulfuric acid, it harbors a biological question mark in those very clouds: Could Venus's atmosphere be a haven for high-altitude life?

Venus is often called Earth's sister planet, and it might also host a biota all its own. While the planet's torrid surface seemingly rules out life, there is a possibility that microbes could live in the more temperate environment offered within the clouds of Venus, a hypothesis put forth by astronomer Carl Sagan in 1967.

That prospect is propelling the first private mission to Venus, an endeavor outfitted with high-tech instrumentation designed to search for signs of life in its clouds by detecting organic chemistry.

Sara Seager, a professor of planetary sciences at the Massachusetts Institute of Technology (MIT) is the principal investigator for the series of Morning Star missions to Venus, which will deploy a small, nose cone-like probe crafted to sample the Venusian atmosphere using something called an autofluorescence nephelometer. That instrument can measure individual particles in Venusian clouds, detailing their size, shape, and composition in a search for signs of organic molecules.

NASA/JPL-CALTECH/USGS



LIFE IN THE CLOUDS The Morning Star missions depend on the data that will be collected using an autofluorescence nephelometer (AFN). The AFN, shown here, can measure individual particles, collecting information about their size, shape, and composition.

TED FISHER AND DARREL BAUMGARDNER, CLOUD MEASUREMENT SOLUTIONS

THE VENUS PROBE is now resting in the Long Beach, California, headquarters of Rocket Lab, an entreprenurial space launch firm that's providing the launch vehicle for the mission with Seager's MIT lab. In a launch that is planned for 2026, a Rocket Lab booster will hurl the exploratory craft to Venus to begin the first privately funded investigation of that planet.

After it reaches Venus, the 37-pound probe, which measures just 16 inches across, will plunge into the planet's wild and wicked atmosphere for roughly five minutes. During its descent it will scan for evidence of organic molecules within the cloud layers that hover from 28 to 37 miles above Venus's 854-degrees-Fahrenheit surface.

Inside the probe is a spherical pressure vessel that maintains a temperature suitable for its onboard electronics and instrumentation. Information on what the probe finds during its searing freefall will be transmitted directly back to Earth by a small antenna. To protect the probe from the high temperatures of Venus, engineers at NASA's Ames Research Center in California's Silicon Valley designed and built its Heatshield for Extreme Entry Environment Technology (HEEET). This shield is made of a woven material fabricated to withstand temperatures up to 4,500 degrees Fahrenheit as the probe navigates the extreme friction generated by piercing Venus's atmosphere at high speed.

"It's worth going to look more closely for signs of life."

Funding for the Morning Star mission to Venus, specifically the scientific equipment and research support for the investigation, was provided by Schmidt Sciences.

Schmidt Sciences knew there was something appealing about one of Earth's nearest neighbors, Seager says. "Even if there's no life on Venus, that's fine. It would be dumb of us not to try. We know there's interesting chemistry that we don't understand. So either way, it's a win to go back to Venus."

The lead of astrophysics and space at Schmidt Sciences is Arpita Roy, a former tenure-track astronomer in NASA's Space Telescope Science Institute and a dedicated specialist in habitable zones and exoplanet discovery.

For Roy, Seager's proposal for funding the exploratory trip to Venus was ideal as "it fit into our parameter space of interest." The mission would be relatively fast, and it didn't require any fancy new technology to collect unique data, as the autofluorescence nephelometer makes use of off-the-shelf instrumentation, she explains.

"We liked how plucky and still brave it was, this return of in situ Venus measurements after so many years," Roy says.

The first successful flyby of Venus was completed by NASA's Mariner 2 spacecraft, which buzzed past the planet in 1962. Other spacecraft dedicated to purging Venus of its secrets were flown and funded by the United States, the former Soviet Union, and Europe, with Japan launching the most recent mission built to specifically survey Venus in 2010.

The other thing that Roy says is very cool about the new mission to Venus is sorting out which data, during the probe's five-minute plunge, is exciting and convincing enough to merit going back, perhaps over and over again.

MOST PEOPLE VIEW VENUS as a scorching-hot hellscape, a planet ravaged by a runaway greenhouse effect. However, this second rock from the sun is receiving more and more attention these days as a potential abode for alien life.

For instance, in September 2020, researchers at MIT and Wales' Cardiff University announced that they had spotted phosphine in Venus' atmosphere by way of ground-based observations. The published finding was a magnet for attention because, here on Earth, phosphine is typically produced by living organisms. But the Venus phosphine claim remains in question, is contested by some researchers, and demands further investigation.

MIT researchers have also suggested the presence of an unknown chemical in the high-altitude clouds of Venus, one that absorbs more than half of all ultraviolet radiation buffeting the planet from the sun. Researchers have puzzled over the identity of this UV absorber for more than 30 years, with some scientists suggesting that the compound could be a photosynthetic pigment produced by Venusian cloud-based life.

FEARLESS LEADER Sara Seager, seen here working in the lab, is the principal investigator for the Morning Star series of missions to Venus. "The fact that Venus is kind of a living, breathing planet is pretty compelling," she says.

More recent news from Venus is highlighted by Seager. "Now researchers are more sure that there is volcanic activity," she says. Because volcanoes help regulate a planet's atmosphere by cycling gasses, such as carbon dioxide, and their associated tectonic activity shuttles crucial chemicals from interior to atmosphere, planets with volcanic activity are typically considered good candidates for hosting life. "So the fact that Venus is kind of a living, breathing planet is pretty compelling," Seager adds.

THE MORNING STAR MISSION features an autofluorescence nephelometer, or AFN in space shorthand, a device that will hopefully help untangle some of these chemical mysteries. That instrument will shine a laser through a tiny, sapphire window. The laser light will scatter off particles floating in Venus's clouds and bounce back to the AFN, which will measure the backscattered light.

Seager says that mission researchers tuned the wavelength of the laser light produced by the AFN to illuminate organic molecules that emanate from biological entities. "It can confirm the cloud particle size distribution and what the cloud particles might be made of," she notes. "Pure sulfuric acid will not show fluorescence. Autofluorescence is the natural fluorescence of biological structures. If we actually see fluorescence, it won't tell us what organic particles are there," she adds, "but it will indicate there are organic particles."

Seager and colleagues reported in a 2023 *Proceedings of the National Academy of Sciences* paper the results of lab experiments that showed nucleic acid bases, key molecules needed for life, are stable in concentrated sulfuric acid. "The stability of nucleic acid bases in concentrated sulfuric acid advances the idea that chemistry to support life may exist in the Venus cloud particle environment," Seager and colleagues concluded.

IAROSLAV IAKUBIVSKYI

Did conditions on the planet short-circuit attempts at microbial life in the past?

So could such an aggressive solvent in the hazy clouds of Venus be a friendly environment for alien biochemistry? "Our finding," Seager says, is the most convincing piece of evidence that suggests "it's worth going to look more closely for signs of life."

NASA'S LAST DEDICATED MISSION to Venus was the Magellan orbiter released from a space shuttle in 1989. It imaged the entire surface of Venus with its cloud-cutting radar system, teasing out a slew of findings, such as evidence of volcanism, lava channels, pancake-shaped domes, and turbulent surface winds.

While there are multiple missions to Venus now on the books, whether current NASA budgetary woes translate into building, launching, and flying them is uncertain at best.

Here's the newly imperiled U.S. government-supported manifest. There's the planned 2031 launch of the NASA Venus orbiter, VERITAS (Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy). Work has also been underway on NASA's DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging). This bold mission features a descent probe slated to plunge through the planet's clouds down to its surface. Projected to launch in the early 2030s, DAVINCI would be the first NASA mission to visit the Venusian atmosphere since 1984.

In addition to NASA's solo Venus ambitions, the European Space Agency plans to launch the Envision spacecraft in November 2031. It would study Venus from its inner core to its outer atmosphere. The Envision mission is a partnership with NASA, with the U.S. space agency providing a cloud-cutting Venus Synthetic Aperture Radar (VenSAR).

ENTER THE MORNING STAR missions to Venus. This private effort is exciting for two reasons, says Paul Byrne, an associate professor of Earth, environmental, and planetary sciences at Washington University in St. Louis, Missouri.

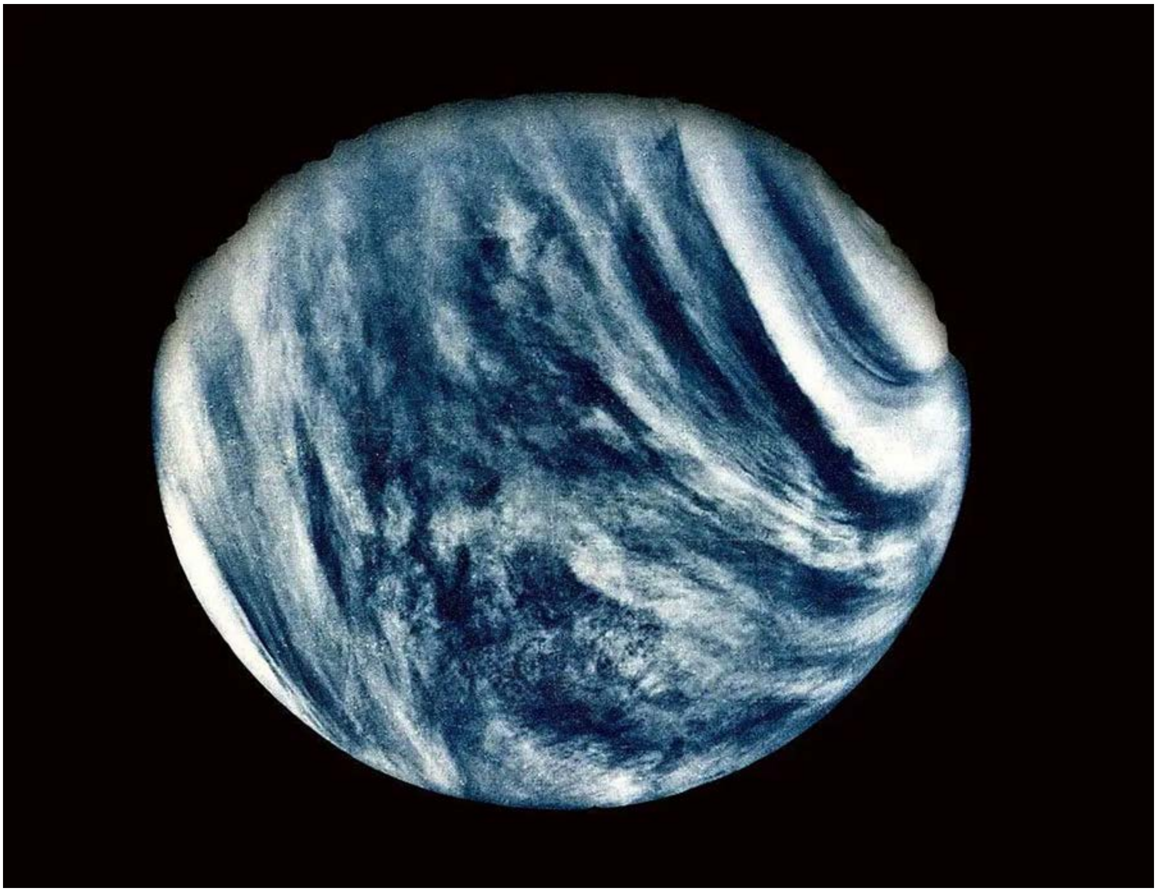
For one, the idea that Venusian clouds might be habitable is a tantalizing one, since Venus isn't the first place we think of when the word "habitability" is mentioned, Byrne says. But the skies above Venus represent the only other environment in our solar system where temperatures and pressures approach those that exist at Earth's surface.

"There are challenges to life there, including high ultraviolet radiation, very little water, and the possibility that any nutrient supply there might be extremely limited," says Byrne. "But that's the point of this mission—to see just what's there."

Byrne adds that the idea of scientists partnering with industry to carry out the first private interplanetary mission sends a very encouraging signal that this model of exploration is worth pursuing. Indeed, that signal comes at a time when both commercial activities for the moon are ramping up and NASA's science budget is facing an existential threat, he notes.

While the private Morning Star mission is a short-lived jaunt into Venus's atmosphere, Byrne's view is that it might be enough to answer a fairly profound question: Is there life there? And efforts such as these are even more important in light of the recent drastic cuts to NASA.

"It is worth bearing in mind that Venus is a criminally underexplored place, and just as NASA started to get momentum building for a return to the second planet those plans look to be facing the axe," Byrne



LIFE IN THE CLOUDS?
Though the surface of Venus is boiling hot, conditions in the persistent layer of swirling clouds could be just right to host life.

cautions. Because the projected renaissance in Venus exploration blueprinted by NASA may not materialize, he says, the Morning Star approach mission "is a welcome step in getting to know our nearest planetary neighbor—and the only Earth-size world we will ever visit—a little better."

JAMES GARVIN, CHIEF SCIENTIST at NASA's Goddard Space Flight Center and principal investigator of NASA's DAVINCI mission, agrees that the time is right to explore Venus' secrets more carefully. Another bold question researchers can ask about Venus is how a planet may have lost its habitability, he says. Did conditions on the planet short-circuit attempts at microbial life in the past? Or maybe Venusian lifeforms found a way via chemical refugia in the atmosphere to preserve aspects of what once was.

"Perhaps Venus offers a perspective on this key ingredient in our home planet as a life-infested world by allowing us to see other evolutionary pathways," adds Garvin. "My hope is that the world space exploration community considers the incredible possibilities presented by Venus as a relevant piece of an emergent exploration agenda."

NASA/JPL-CALTECH/USGS

Could the hazy clouds of Venus be a friendly environment for alien biochemistry?

In Garvin's view, Venus is a natural laboratory waiting for scientists to fully explore its multi-layered but intriguing atmosphere as its deepest parts lie unexplored, much like Earth's deep sea.

Venus, he says, is "deeply mysterious and awaiting explorers to read its chemical fingerprints and interactions to learn how to explore on the edge with new capabilities that offer benefits here on Earth and beyond. I can promise you; Venus will not disappoint!"

According to Richard French, Rocket Lab's director of space systems business development and strategy, the Venus mission is an example of what is now possible. "Even with the mass and data rate constraints and the limited time in the Venus atmosphere, breakthrough science is possible," he explains.

THE MISSION TO VENUS is clearly an ambitious venture, but with a clear hypothesis: There is no life without organic chemistry. Saluting the science team behind the mission, French says he believes that any detection of organic chemistry makes the presence of life more likely.

The success of the mission is dependent on details relayed back to Earth from the probe's dip into the Venusian atmosphere. But finding some intriguing trace of organic molecules is just the beginning. The team will also face the challenge of relaying such insights to the general public.

MIT's Seager reports that the Venus-bound probe is now being prepped for sendoff and has been delivered to Rocket Lab's facilities in Long Beach, California.

"Think about it. We haven't visited the atmosphere of Venus with modern instrumentation. It has been decades … and we see all this mysterious chemistry there," says Seager. "The first mission will definitely confirm, refute some existing knowledge, and find some new things."

Seager, already busy at work plotting a follow-up Venus investigation, acknowledges that the maiden voyage of the Morning Star series of missions to Venus is not going to be a slam dunk given that it represents a modest scientific trip to the planet for cloud data.

But the mission will be a resounding success if probing the planet's clouds reveals definitively that there's complex organic chemistry happening in the cloud particles, Seager says. "It will be a game changer to show that for real, not just in the lab or in our minds."

LEONARD DAVID is an award-winning space journalist who has been reporting on space activities for over 50 years. He has authored numerous books and articles focused on space exploration, including *Moon Rush: The New Space Race* and *Mars: Our Future on the Red Planet*, both published by *National Geographic*.

The Power Grid Is Struggling. Can AI Fix It?

Renewables, EVs, and AI itself are straining the grid. These researchers have ideas to evolve it.

BY SOFIA QUAGLIA

THE POWER GRID is a puzzle. A patchworked network of hard infrastructure, software, and growing demands at nearly every node. It was a difficult enough system to operate when the inputs were regular. Now, however, as more fluctuating—but increasingly essential—renewable sources, such as wind and solar enter the grid, the equation gets even messier. How can the dated grid evolve to keep pace with the future?

Some researchers are turning to AI in a bid to help keep the lights on.

Most power grids in the United States were built before the 1970s—when power came from coal and gas plants that ran all day and all night with fairly clockwork predictability. So power grids were designed to take energy from those centralized, stable sources and distribute it around the country on one-way, road-like cables. Job done.

Now energy isn't generated just in a handful of coal- or natural gas-based power plants. It is absorbed from the sun in solar panels across countless rooftops or farmed from the wind with thousands of turbines spotting rural fields. This means there are loads of scattered and disconnected points of entry to the power grid, and energy is flowing in several different directions and not just one unified stream.

These new clean energy sources also aren't always on. Weather is fickle: Wind comes and goes, and the sun rises and sets every day, but sometimes it is cloudy. And we don't yet have adequate energy storage technology. We can't reliably and at scale store excess sparks from an extra sunny week, or dip into a reserve when the gods of wind aren't in the mood for gusts.

All of this is at fundamental odds with how the current energy grid works. "The grid requires this really perfect balance between demand and supply," says Anna Scaglione, a professor of electrical and computer engineering at Cornell University.

And this is being additionally challenged with an increase in energy demands. In 2024, humanity's need for energy spiked by about 4.3 percent, according to the International Energy Agency—that's nearly *double* the yearly average from a decade prior.

More everyday vehicles and appliances now run on electricity as opposed to gas. Even coping with climate change pulls more power: The summer 2025 heatwaves in Europe increased the daily power demand by up to 14 percent. And some U.S. states are now using fossil-fuel plants to make enough electricity to produce electric vehicles. Daily tech, too—from video streaming to AI chatbots—demands still yet more power, with data centers forecasted to increase energy demand by a whopping 20 percent by 2030, when they'll likely be consuming globally as much energy as the whole country of Japan does today.

"When we switch the lights on, we are not aware, but sometimes there is congestion on the grid," says Scaglione. And that congestion, when taken to the extreme, can bring whole systems down.

As a result, sometimes entire countries are left struggling to keep the lights on. For example, this spring, Spain and Portugal had massive blackouts in which 55 million people were left powerless because their grid struggled to handle renewable energy's swings (among other technical issues). Blackouts like these are going to become increasingly more common, says Scaglione, if we don't upgrade our grids in thoughtful ways.

Improving outdated grids to meet the twin challenges of increasing demand and fluctuating, distributed inputs requires a lot of strategy and complex computation. But scarcity is the mother of invention, and energy experts around the world are adding more computing power through AI to tackle different challenges at each step of the system.

ON ONE LEVEL, evolving the grid is about incremental physical improvements. For example, bolstering the capacity to transmit energy from the places where renewables are burgeoning. "We need to build out new transmission corridors to access renewable-rich zones, like the Great Plains and parts of the Midwest and the Southwest," says Tyler Norris, a doctoral student and grid transition researcher at Duke University's Nicholas School of the Environment. And implementing better conductors that can carry more energy overall, Norris says, "basically installing a fatter wire that can accommodate more power."

Better storage capacity, too, will help, holding onto energy while it is plentiful and not in high demand. This means improving and scaling up traditional lithium battery banks, as well as developing new forms of energy storage, such as solid-state sodium-based batteries (sodium is far cheaper, safer, and more widely available than lithium) and vanadium redox flow batteries, which work by storing energy in liquid electrolytes instead of solid electrodes like in lithium batteries.

We can also improve how we draw electricity from the grid. Human societies tend to fall into relatively broadly predictable patterns, so there are times of known higher energy use—like frigid winter mornings, between 6 a.m. and 9 a.m., which is what most power

METAMORWORKS / SHUTTERSTOCK

grids are tailored to cover—and known lower ones. “About 80 percent of the time, a third of the power system sits unused,” says Norris. “That’s a really inefficient use of resources.”

Smart devices can automatically adjust things like thermostats to adapt and adjust around peak energy-use times to put less strain on grid demands—and hopefully help avoid large-scale blackouts. “You are going to obviously notice if the light is not on, but as long as your air conditioner keeps you within your comfort temperature, you don’t notice when the vent is activated or not,” says Scaglione. That’s true of anything that is thermostatically controlled, including air conditioners, water heaters, and heat pumps. These can be designed to make the temperature just right while there is less congestion on the grid, and right before energy rush hours.

Electric vehicle charging hubs can also work similarly, with smart timers that gauge the amount of demand on the grid and charge when there is lower need. “There is going to be a lot of technology that will be integrated more into general appliances,” says Scaglione. “It will be interestingly orchestrated by these algorithms that will use some artificial intelligence to make predictions about energy use.”

BUT MORE IMPROVEMENTS will come from optimizing within the grid itself—using AI to improve the grid’s situational awareness and near-term prediction of power production and demand; planning and building out grid infrastructure and markets; and streamlining operations by improving real-time decision-making, says Priya Donti, an assistant professor at MIT’s electrical engineering and computer science department and the Laboratory for Information and Decision Systems.

Donti is a 2023 AI2050 early career fellow, a program in Schmidt Sciences that asks researchers to imagine the year 2050, where AI has been hugely beneficial, and to pursue projects that help society realize this. The program funds senior researchers and early career scholars for two years to address a wide range of global challenges in AI.

Already, artificial intelligence can help quickly crunch the numbers to predict how much renewable energy production the grid will have—by more accurately forecasting weather and climate, for instance—and how much demand it is likely going to have, again, by forecasting weather and similar factors.

For planning, AI can also be used to speed up simulations for how to schedule power on the power grid in real time and applications that simulate what the grid will need in order to be most efficient as it expands. For example: Where should new branches of the grid be built, and how big should they be to accommodate possible renewable inputs and likely energy demands in the future? “That’s like seeing how the effects of your algorithm play out over a longer time horizon,” says Donti—predictive power our previous tech didn’t have.

But even with the most highly tuned AI programs predicting what the grid will need, not everything will go to plan. And AI can also help the grid respond to unforeseen situations in real-time.

“There are some true physics that govern how the [power grid] behaves, but we use all sorts of approximations to solve them,” says Donti. “The gap between those approximations and reality is becoming more and

more punishing as we're starting to deal with a system that's more complex."

So Donti's laboratory is working to create faster, more accurate algorithms for power grid management while maintaining physical realism. While current grid algorithms use approximations that sacrifice accuracy for speed—flattening non-linear physics into linear equations that are easier to solve using traditional computational techniques—her AI-powered algorithms are equipped with more realistic features that are true to the complicated intricacies of the physics at hand. She trains AI models ahead of time to learn almost all of the possible grid scenarios and optimal responses, so that solutions can be applied more quickly than if it were trying to solve the original problem from scratch every time, Donti says. "Now you have almost like a bucket of strategies," says Donti. "Then in real time, when you see a particular problem happen, you're like, 'Oh, I'm just going to pull this out of my bucket of strategies.' "

This also involves increasing how much flexibility we give the grid. Instead of checking in on the grid's performance at intervals of hours or even days, as many of our systems are currently programmed to do, embedding AI in the operational algorithms can help move toward a future where they are checking on the grid almost continuously, looking for changes or problems right on the spot.

Donti compares it to scheduling your week—you might think you know what your week is going to look like, but if anything comes up in real time, you usually adjust accordingly. "You go based on what's actually happening," says Donti. Now imagine that you are restricted, so that if something comes up urgently, you cannot deal with it immediately and schedule the rest of your day around it. "You're like, nope, you're not due to reassess what your schedule looks like for another 50 minutes," Donti says—that's what the grid is like now, and what AI could help overcome.

"We could get different components of the power grid to be able to reassess how the grid is coordinated, given real-time information," says Donti. AI can help devices like batteries and generators make immediate decisions about storage and power creation based on current grid conditions.

This level of real-time reactivity also enables having a more distributed grid. Instead of everything needing to be centralized, there could be small, scattered AI systems that integrate information from local community needs and then make changes just to that segment of the grid—not having to go all the way back to centralized power, and, in an extreme example, shutting down the whole country's electricity if something goes wrong.

> *Spain and Portugal had massive blackouts in which 55 million people were left powerless.*

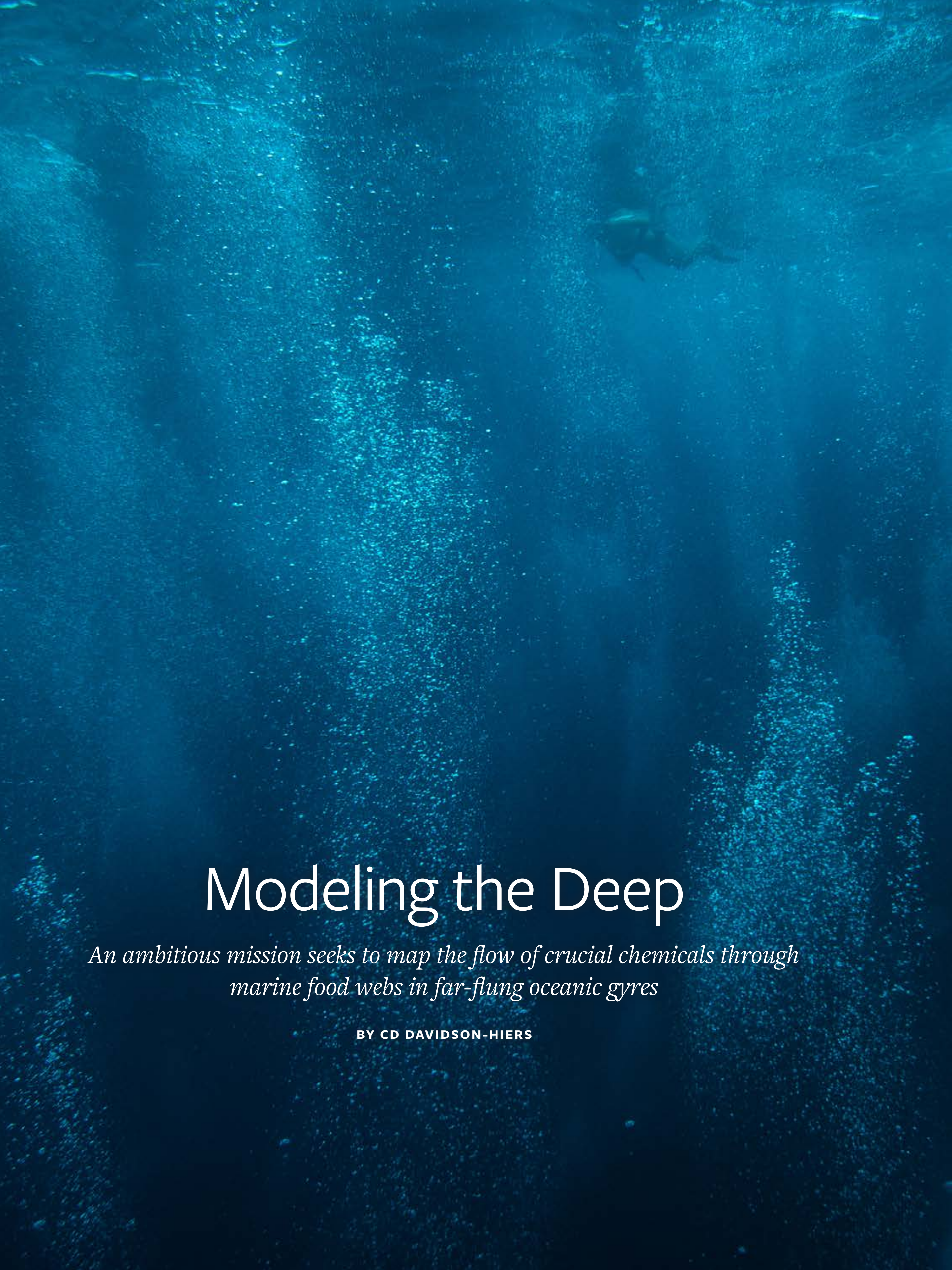
DONTI AND OTHERS are hoping AI can help pave the way for a more resilient energy future. Still, there is work to be done, and in order to create and validate machine learning algorithms in these areas, you need good data and good simulation environments to test out all of these algorithms and see if they work, says Donti.

"Our simulation tools right now are fairly early, and so we are just looking at a longer, longer horizon," says Donti. "On the other hand, I think we can't really afford a longer horizon, so there has to be some really deep intervention to try to really improve the state of data and simulation environments."

Plus, she and other scientists haven't forgotten that the very data centers needed to run AI are also, ironically, one of the largest things currently causing strain on the grid. So data centers will also have to lead the way in how they optimize their energy use, says Scaglione, because they'll need to make sure they're not weighing down the very system they are trying to improve.

SOFIA QUAGLIA is a freelance journalist writing about all things science and nature and how we talk about them. Her work has appeared in *The New York Times*, BBC, *National Geographic*, *The Guardian*, *New Scientist*, and more. She's on a mission to visit the entire planet by spending each month in a different country, so she's been living on the road since 2021. She is also a recipient of the National Academies Eric and Wendy Schmidt Awards for Excellence in Science Communications.

FAHRONI / SHUTTERSTOCK



Modeling the Deep

An ambitious mission seeks to map the flow of crucial chemicals through marine food webs in far-flung oceanic gyres

BY CD DAVIDSON-HIERS

A DESERT IS NEVER BARREN. Life can course through even the most inhospitable landscapes—arid wilderness, Antarctic ice fields, or mid-ocean depths—leaving traces of its presence among grains of sand, ice crystals, and water molecules.

University of Montana professor Matt Church, a marine scientist who studies microbial ecology and nitrogen and carbon cycling, wants to explore how carbon moves through two of the world's five ocean gyres. Swirling across vast distances in the North Pacific, South Pacific, North Atlantic, South Atlantic, and Indian oceans, these are enormous ecosystems defined by massive, circular ocean currents and often compared to terrestrial deserts.

These systems may contain reams of chemical information, especially about how carbon, a building block of life on Earth, flows through our seas and into the depths.

As part of a multimillion-dollar, five-year project funded by Schmidt Sciences last year, Church and a team of 24 people, including nine investigators and various research, lab, and field technicians, are heading to two subtropical gyres—the North Pacific (between the United States and Russia) and the South Atlantic (between South America and Africa) to explore the biology and chemistry of these underexplored areas.

"People think of deserts as barren, relatively devoid of life, kind of harsh ecosystems," says Angelicque White, a biological oceanographer at the University of Hawaii at Manoa and co-lead investigator on the project. "The subtropical gyres are remote. They are generally at latitudes where there's low seasonality, so you have something akin to an endless summer," she adds. "But [like deserts], the ocean gyres actually do have quite a diversity of life that has adapted to those ecosystems."

A single drop of seawater can contain a million bacterial cells.

A single drop of seawater can contain a million bacterial cells, and that's precisely what White specializes in finding and studying. On the other end of the biological size spectrum, these areas of the ocean are also seasonal breeding grounds for whales and other macrofauna.

The $9.5 million project is dubbed the Subtropical Underwater Biogeochemistry and Subsurface Export Alliance (SUBSEA) and is one of five international projects underwritten by Schmidt Sciences that form the Ocean Biogeochemistry Virtual Institute (OBVI) network. Projects under the OBVI umbrella will share information and fill in gaps in research on understanding marine systems, and findings from them will be made publicly available.

"[These projects] collectively aim to advance our understanding of ocean carbon cycling and also the role and response of marine ecosystems to that carbon cycling," says Lexa Skrivanek, program scientist and lead manager for the OBVI program at Schmidt Sciences. "[The projects' goals are] to get a better sense for the oceans' role in stabilizing Earth's climate and then how it may evolve."

THE SUBSEA TEAM wants to understand how gyre ecosystems pull carbon from the atmosphere and move it into the deep sea, a process known as carbon sequestration.

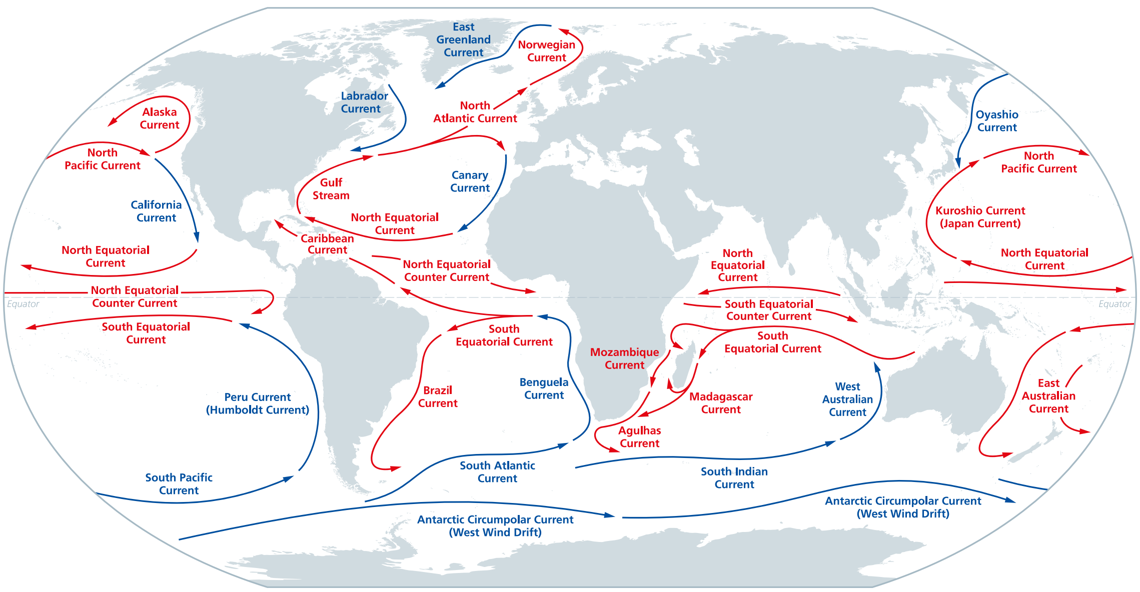
The world's oceans, which cover approximately 70 percent of the planet, soak up and store about a quarter of Earth's carbon dioxide. Human activities since industrialization in the last couple centuries have increased CO_2 emissions to unprecedented levels. All of this excess CO_2 in the atmosphere serves as a blanket that encircles the Earth, causing the planet to retain more heat, raising temperature on land and in the sea.

And as our planet's climate continues to change and temperatures rise, the oceans continually absorb that excess carbon. Somewhat like an antacid pill dropped in a glass of water, CO_2 dissolves into the seas and reacts with water molecules to produce carbonic acid. This acid lowers the ocean's pH, raising its acidity.

But CO_2 is also taken up by microscopic plant cells, called phytoplankton, that use the compound to conduct photosynthesis, transforming that carbon into biomass, with oxygen as a byproduct. One of the goals of the SUBSEA team is to explore carbon flux through the bottom of the photic zone—the depth at which enough sunlight reaches for organisms to function—where phytoplankton manage to harvest enough light to power their photosynthesis. "Our proposal was really to try and better understand productivity in that lower portion of the water of the photic zone," Church says. This deepest layer of the photic zone sits about 300 to 650 feet beneath the surface, making it less studied than shallower regions of the water column that can be tracked by remote sensing tools, such as satellites.

"Still, shallow water relative to the full ocean depth, but in the portion of the upper ocean where light has become low," he adds. "There's still productivity and phytoplankton, and that portion of the water column we don't observe well with satellites."

PAGE 50: OSMAN TEMIZEL / SHUTTERSTOCK



A WORLD ASWIRL

Gigantic circular currents, called gyres, span the planet's oceans. Measuring how essential elements move through these massive swirls of seawater could revolutionize our understanding of Earth's dynamic cycles and systems.

Church says that he and his team plan on using recent advances in satellite technology to probe deeper into the photic zone than ever before with the goal of capturing the dynamics of the organisms that make their homes there and react to Earth's changing climate. "The oceans are warming, so that's going to change the metabolism of organisms and things that I view as the direct impacts of a warmer ocean," he says. "But there's all of these sorts of indirect or non-linear processes that I think we have just barely begun to scratch the surface of thinking about that are potentially super important."

MOST OF THE NUTRIENTS in the ocean move through ocean waters vertically. As oceans warm, the density profile of seawater changes and this vertical exchange becomes more stratified and layers are less apt to mix, like a glass filled with vinegar, water, and oil. "What that means is that the input of nutrients from depth becomes more restricted in these ocean gyres," Church says. Even though abundant CO_2 is available to plankton photosynthesizing in the photic zone, their growth is restricted by the dearth of nutrients supplied to these near-surface layers via upward transport from deeper water.

And this means that the carbon sequestration conveyer belt—with carbon being pulled from the atmosphere and stashed in the deepest depths of the ocean—breaks down. "Those systems, mostly because they're so big, are super important in carbon dioxide uptake by the ocean and its ultimate export to the deep ocean," Church notes. "As you limit nutrient availability because of that stratification, you're actually potentially limiting the carbon sink that the oceans are responsible for, because the biology becomes limited by nutrient input."

More carbon, more heat, more separation, more carbon—and the cycle continues.

PETER HERMES FURIAN / SHUTTERSTOCK

SCIENCE IN A GYRE Members of the SUBSEA team deploying a Wirewalker at the Station ALOHA sampling in the North Pacific Subtropical Gyre. This instrument has sensors that measure key biogeochemical and physical properties of the upper ocean as it moves vertically through the water.

SUBSEA INVESTIGATOR NICK HAWCO

THE SUBSEA PROJECT EVOLVED out of a program called Hawaiian Ocean Time Series (HOTS), which measures ocean biogeochemical processes over time and which White leads. The HOTS program began in the late 1980s and has measured seasonal cycles of biology, chemistry, and physics from Station Aloha located north of O'ahu Island. Many researchers consider the ocean ecosystem at Station Aloha "always blue, always warm, always stratified," White says. "By studying the system carefully for decades, we're now able to understand the seasonality of surface processes, how that interacts with the deeper layers of the ocean."

She focuses on nitrogen cycling, using optical tools, such as underwater vision profilers, video plankton recorders, and an imaging flowcytobot, which captures video footage of organisms for identification, quantification, and to measure their constituent chemistry. For the SUBSEA program, White says she'll get to build on her "very deep love of plankton imagery" using all of these technologies.

She'll take millions of images of plankton—at scales ranging from sub-microscopic to sizes that can be seen by the naked eye. White will then use machine learning tools to classify organisms, such as diatoms with their silica shells, cyanobacteria, or calcifying phytoplankton called coccolithophores. Then undergraduate and graduate students will help the researchers validate the AI model's identifications. "Now, with the support from Schmidt Sciences, we have an opportunity to go out and test these models [with the SUBSEA program]," she says. "And in one of the most underexplored regions of our oceans."

THE SUBSEA RESEARCH TEAM hopes to map out the complex routes that vital elements take from the atmosphere to surface waters to ocean depths and back, traveling through food webs as they traverse vast vertical distances over impressive timescales.

Think of the ocean as a continuum, says Bob Hall, a stream ecologist with an office next to Church's at the University of Montana who will be on the SUBSEA cruise, which is supported by the Schmidt Ocean Institute, next year. "If you were to put a water molecule 1,000 meters down, it's going to be a long time before that water molecule ever mixes toward the surface ... before that ventilates with the atmosphere," he notes.

The SUBSEA team aims to get an unprecedented handle on the parameters of global nutrient cycles, which could eventually lead to the ability to predict future trends in several biological processes, such as oxygen production, productivity, and carbon sequestration, as the climate continues to change, Hall adds.

As the ocean stores (and cycles) nearly 50 times more carbon than does the atmosphere, it acts as a

IT'S A TRAP (ARRAY) Sediment trap arrays like this one, being sent into the North Pacific Subtropical Gyre from the SUBSEA team's research vessel, collect sinking particles that will be analyzed to determine how elements like carbon, nitrogen, and phosphorus travel from upper ocean to the interior waters of the ocean.

SUBSEA POST-DOC ALEXIS FLOBACK

biological pump we don't fully understand. Though oceanographers have long studied large- and small-scale marine processes, previous research has not paid much attention to the subsurface layer that the SUBSEA team wants to model, says chemical oceanographer Weiyi Tang of the University of South Florida.

"I was really amazed by the amount of work they proposed to do," he says, noting also the project's international scope and its cutting-edge technology. "That can potentially stimulate the development of technology in the future—how humans can potentially better observe the ocean, particularly its changes."

The project's implications could affect current and developing industries that depend on predicting the behavior of Earth's oceans in the face of mounting uncertainty. Tang points to commercial fisheries, aquaculture, and the rapidly growing seaweed farming business. The ocean supports a global economy, and contains the foundation for supporting life on Earth, he notes.

"But looking to the future, the [SUBSEA project] may open new industries or new revenue by exploring the oceans' ecosystem services," he says.

ALREADY A YEAR INTO their five-year plan, the SUBSEA team is hard at work building on their current research and preparing for their first voyage next year. It's a massive undertaking, considering the onboard technology alone. The tools the researchers will use to complete their ambitious mission include underwater autonomous crafts, profiling floats, wirewalkers—which contain oxygen sensors, fluorometers for measuring how light travels through water and organisms, and can quantify temperature and salinity—and sediment trap arrays, widely used by oceanographers to measure particle flux, which will drift from their ship on a tether. The researchers will also depend on eyes in the sky, tapping into a NASA-launched satellite that's part of the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission that launched in February 2024 and helps record satellite observations globally of ocean biology, clouds, and tiny atmospheric particle aerosols.

In addition to the tools needed to complete their mission, White, Hall, and Church will be accompanied on the cruise by researchers hailing from institutions in Argentina and South Africa. "These international partnerships are greater than the sum of our parts," White says of these cross-border collaborations.

The SUBSEA team will set off on the first of two sea voyages in March 2026 for a 35-day field cruise on a research vessel called the *Falkor* (*too*). Church says he hopes the scientists can visit five different locations in the subtropical North Pacific and South Atlantic gyres for about five days each. Right now, though, he's busy figuring out how to ship a 40-foot container through Brazil to their departure port in Rio de Janeiro.

Despite the logistical challenges, the team is eager to launch the mission and start collecting data. "I feel honored in many ways that [Schmidt Sciences] selected our project," Church says.

In four years, the SUBSEA project could help construct a better understanding of the intricate chemical cycles suffusing the ocean's many layers, and how one of the most important elements of life on Earth flows through them.

CD DAVIDSON-HIERS is a Florida journalist and essayist.

How AI Is Helping Archaeologists Make Discoveries

New clues about ancient civilizations are being unearthed from the data

BY LINA ZELDOVICH

ARCHAEOLOGIST JESSE CASANA was scrolling through thousands of aerial images on his computer looking for signs of ancient sites. The images, taken from planes and drones over the Middle East, harbored definitive evidence of old Roman forts. But spotting them required the trained eye of a seasoned archaeologist. And hours and hours of time.

Archaeology happens at many different scales—from the single shard of pottery to full landscapes and networks of civilizations. Each has its own challenges, and for Casana's work, one of the big challenges was volume. He was up to 400 forts with at least a couple of thousands more to go—tedious work that was taking a long time. "I've been doing this my whole career, I go fast, and I'm good at finding things," he says. "But this was a really big area, and I could use some help."

At the time, in early 2023, Casana, founder and director of the Spatial Archeometry Lab at Dartmouth University, didn't have many options. He tried enlisting his students to help, but that didn't work well. "They were very earnest, but not very good," Casana shares. "They missed real forts and found things they thought were forts, when they weren't. I had to redo their work." He was thinking about what else he could do. And then he had a Eureka moment.

It was right around then that AI-powered tools, such as ChatGPT, began surging into everyday life, answering questions, writing term papers, and even detecting tumors in medical images. Casana wondered if he could train an "AI-rcheology" model to spot archaeological sites to speed up the process. "I was hoping I could get a new AI friend that is almost as good as me."

Archaeology may not always come to mind as a hotbed of high-tech work. We've been trained by books and movies to conjure archaeologists burrowing into the ground in deserts and valleys in remote parts of the world, unearthing ancient objects, dusting them off, perhaps hand-writing some field notes.

PAGES 56-57: STOCKSTUDIO AERIALS / SHUTTERSTOCK

"The very first aerial photos of an archaeological site were taken over Stonehenge with a hot air balloon."

Casana, however, would like to correct this misconception. Archaeologists have always been keen on technological advances, he says. And not only for time-saving reasons. Being able to study relics of the past—from cities to structures—from a distance also avoids many challenges inherent in digging things up, including access to land, the ethics of artifacts, and the labor itself. As the field of digital archaeology has taken off, enabled by drones and new imaging technology, AI has emerged as the next promising tool to help scientists comb through the vast troves of data. But it, too, comes with pitfalls, and some experts say it should be used with caution and supervision.

ALMOST AS SOON AS ARCHAEOLOGISTS could get a bird's eye view of sites, they leapt at the chance. "The very first aerial photos of an archaeological site were taken over Stonehenge with a hot air balloon, before planes were even invented," Casana says. Once planes and satellites began to fly, archaeologists started using even more aerial imagery. As Geographic Information Systems (GIS) became widely available in the second half of the 20th century, it became a tool, too, almost as essential as the old fashioned pick and hammer.

Camera-carrying drones now let researchers peek at places they couldn't access before. Thermal cameras enabled them to see walls and other stone objects buried underground—because rocks heat up and cool off differently than the surrounding dirt, giving off different thermal signatures. Ground penetrating radar (GPR) uses electromagnetic pulses to reconstruct what's beneath the soil, allowing one to see even more over large swaths of land. Light detection and ranging or LIDAR uses laser light to measure distances, allowing researchers to create 3-D maps of landscapes, revealing hidden structures and features beneath vegetation or soil.

Buried in that digital information, archaeologists have been diligently digging from under it—but that takes time. In the years preceding widely available AI, they tried teaching computer systems to identify the spots of interest in that data deluge. "The archaeologists were very enthusiastic adopters of the idea that we could get the computer to do the work of finding things in the imagery," Casana says, but the early attempts foundered. "I was a famous skeptic of these approaches," he shares. "I published two papers in which I talked about how disappointing they were."

EYES IN THE SKIES Archaeologists have been using aerial views to assist with their work since the days of the early hot air balloons. Since then, different imaging technologies have improved their abilities to find and study ancient sites like this one, a Roman site in eastern Syria. The next frontier is AI.

For most of his career, Casana advocated for what he brands as the "brute force" method. "If you want to find the stuff, you should just look at everything with your eyes," he says. "But now, I realize that I might be wrong," he says, especially with new AI systems that can learn from human feedback and from their own mistakes.

THE EASIEST WAY TO TEACH AI to identify specific objects is to train it on objects that are highly regular, says Emily Hammer, associate professor of digital humanities at the University of Pennsylvania. For example, some temples may have similar features, but they may differ, too, from site to site or over time periods. "That's a big problem with archaeology because the past is not regular," Hammer says. But there are some exceptions. For a few years, Hammer has been working on mapping caravanserais in Afghanistan—ancient hotels that dot the Silk Road, a trade route that connected the East and West for centuries.

The caravanserais have a typical structure, Hammer explains. There's a road that leads in through a monumental entrance. There's a courtyard in the middle, surrounded by rooms. There are places to house the pack animals that carried the goods. "These things tend to be of a fairly regular size, and they were built along the roads in isolated areas," says Hammer. All these characteristic attributes make caravanserais an easier training model than rarer structures.

Hammer's work on these structures focused on Afghanistan, but caravanserais existed all over Central Asia, so once trained, the AI will be able to plow through hundreds of thousands of old photos and maps and point archaeologists to the previously unknown sites. "We are planning to use Soviet maps that were

MAXAR (2018)

Thermal cameras enabled them to see walls and other stone objects buried underground.

created in the '40s through '60s," says Hammer, referring to a future project she and Casana are hoping to do together. "These Soviet cartographers were incredibly skilled," she adds, so the maps are of very good quality.

The recently declassified spy aerial photos from the mid 20th century can help, too. In fact, they may be a veritable boon for digital archaeologists because they captured part of the world that no longer exists. "People don't realize the degree to which the archaeological record has been destroyed by mechanized agriculture, irrigation, the expansion of cities and industrialization," Casana says—particularly in the past few decades. But the sites remain preserved, in a digital way, in the old, recently declassified photos.

"That's where AI can do a better job," says Hammer. "It could find them where we know they were. And then we can use it to search on a much broader scale, at the level of countries or continents, because we can't do that with our own eyes."

This project is one of 10 initial projects supported by the Humanities and AI Virtual Institute (HAVI) at Schmidt Sciences, which provides funding for research that brings together AI experts and humanities scholars to unlock secrets of human history and culture.

DEVELOPING ARCHAEOLOGICALLY SAVVY AI models offers other advantages. AI may allow scientists to reduce the number of excavation projects. "I used to run big excavations in the Middle East for many years," Casana says. "A lot of people assume that, as an archaeologist, my goal is to dig a hole in the ground, but really, if I never dig another hole in the ground, I'll be okay with that."

That's because there are better ways to learn about our past than digging through dirt, he explains. Excavating is far from ideal. It creates ethical problems, as many communities don't want to disturb the sites. Some sites are on private land, which is usually off limits. Once you dig up the hole, you can't "un-dig it," so if you make mistakes, such as accidentally breaking a structure, you can't redo it. The excavating process is time consuming and labor intensive, which makes it very expensive. Plus, it produces an enormous number of artifacts that must be taken care of indefinitely—preserved, cataloged, and stored in proper conditions somewhere.

Which is another reason Casana and others have been embracing digital archaeology methods, which are cheaper, faster, and less destructive. "With these new technologies we can learn about the human past without ever disturbing the soil," Casana says. "We record it, we map it, we interpret it, we take only data, we leave only footprints, and we get out of there. That's my preferred way to do archaeology today."

Hammer doesn't think that remote imaging and AI analysis will entirely replace excavating. Digital tools generate a "flattened" picture of what's underground—they compress centuries and even millennia together. Researchers can't yet fully tell from the digital images whether a site was originally a small village that grew into a big city, or whether the city shrank over time.

PATTERN HUNTING AI still doesn't have the nuanced interpretive skill of a trained human archaeologist, but it is a workhorse at finding patterns in images, and spotting similar structures within large expanses of land, such as these ancient Roman Forts.

CASANA ET AL. (2023)

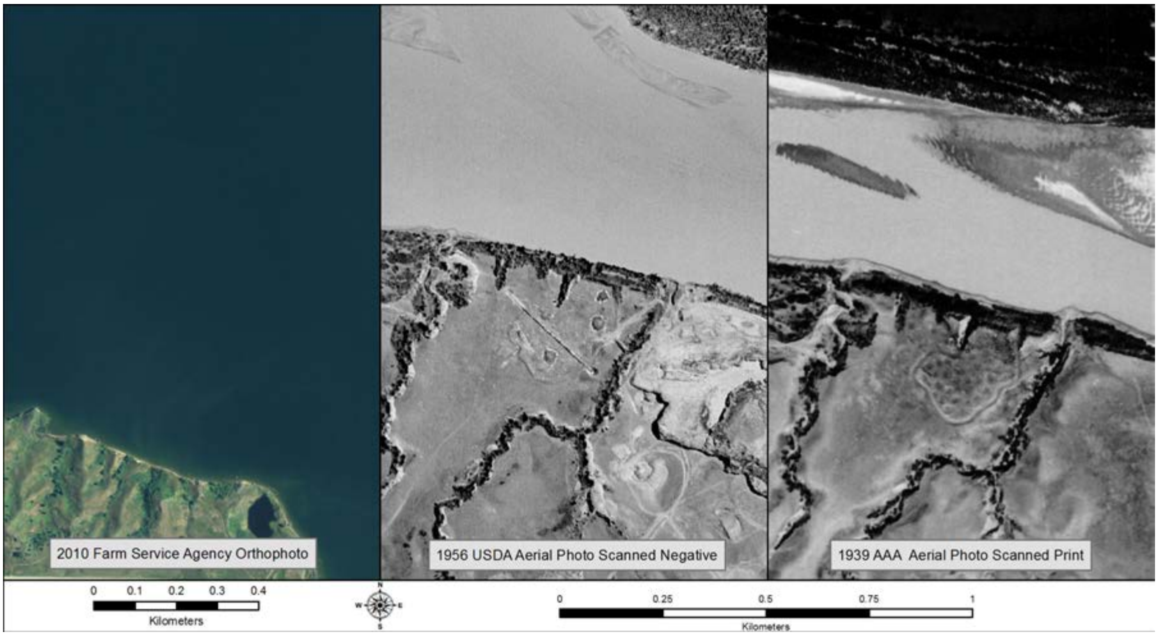
Physically uncovering layers allows archaeologists to understand the chronology of a site and date the materials they find in the proper order, which is key for understanding the trajectory of an ancient settlement or a society.

"As digital archaeologists, we believe in the power of our tools to tell an important part of the ancient story, but I don't think we're ever going to replace going into the field," Hammer says. "If we were to conflate things that happened in one place, we wouldn't have an accurate picture of history at all, without excavation."

There is still more due diligence that AI and remote-sensing can't replace, Hammer says. "I also don't think we should be interpreting history without the knowledge of people who live on that land and probably consider the people of the site to be ancestral to them in one way or another."

Keeping humans in the loop is crucial to avoid perpetuating biases that exist in the archaeological field today, says Colleen Morgan, a senior lecturer in digital archaeology and heritage at the University of York in the United Kingdom.

This is particularly important when turning to AI to take the next creative leap in interpreting the past—not just analyzing images, but generating them. Even before AI, many human-created visualizations of past societies were often biased, for example, depicting only men hunting, making tools, or performing rituals, Morgan notes.



DIGGING THROUGH DATA An unexpected source of archaeological new revelations are old aerial images, such as these, spanning more than seven decades. Water has consumed this site, but early and mid 20th-century images reveal clues as to what was there long before. AI can help sort through mounds of these records to help tip off humans for a closer look.

CLARK AND CASANA (2016)

"These reconstructions do not reflect scientists' nuanced understanding of the past. We know humans organized themselves in an incredible array of variety, with a multitude of gender roles and self-expression," Morgan wrote in a recent essay in *The Conversation*. "Generative AI has both fascinating potential and enormous risk for archaeological misrepresentation."

Hammer suggests that, when used thoughtfully, AI could also help reduce some biases. Historically, archaeologists have favored certain types of places for studies. "They like to excavate temples and wealthy tombs and palaces, so the everyday person's life is sometimes left out of that narrative," Hammer says. AI might be more able to help find more subtle structures, for example, the places where an average person lived.

For their work on new "AI-rcheology" models, Casana and Hammer aren't planning to give AI a lot of interpretational power. Its main task will be to quickly analyze reams of information and present its findings. "And then I, a human, can take that information and make some meaning from it," Casana says.

This is how the real magic usually happens in archaeology, he notes, including excavations. "We dig some holes and find some things, but then we have to explain to people why this is significant and interesting," he says. It takes people to interpret the lives of those who had been there before us, he adds. "And this will remain the job of humans."

LINA ZELDOVICH is an award-winning science journalist and author. Her prior book, *The Other Dark Matter*, has been optioned for a TV series. Her new book, *The Living Medicine: How a Lifesaving Cure Was Nearly Lost—and Why It Will Rescue Us When Antibiotics Fail* was published in October, 2024.

WENDY SCHMIDT

The co-founder of Schmidt Sciences on curiosity, discovery, and wonder

BEN GIBBS

DISCOVERY ILLUMINATES THE WORLD

With the emerging tools of AI, machine learning, space telescopes, and so many others, it's clear that we are just beginning to understand the universe we live in—from the farthest reaches we can find in space, to the smallest quivering particle we now know can be in two places at the same time.

In my lifetime alone, scientists have made enormous strides in the way we treat disease and manage illness, and in the way we see and understand the natural world and the universe. Every time we look more closely at the world around us, we make discoveries. Schmidt Sciences' programs are peering into the depths of space at higher resolution than ever before, and finding biomaterials to replace fossil-fuel products, and seeking to understand, apply, and ensure the safety of the technologies that are transforming our world.

FROM SEA TO SPACE

The ocean is our planet's last frontier, and the opportunities for discovery at sea are as plentiful as they are in space. These two domains, the Earth and space, understood together, comprise the human environment that we increasingly need to understand and protect. This is our life support system, and throughout, we seek knowledge and breakthroughs wherever they may be.

Our climate team explores how human activity affects our planet, and how the planet strives to maintain balance in all its systems, including within the ocean, by cycling carbon and other essential elements. And our astrophysics and space focus area is advancing technologies based on the ground and in space to seek answers about our universe. However distant these two arenas may seem—ocean and space—our teams share a similar approach and spirit. They're asking the biggest questions, spurring interdisciplinary collaboration, applying new technologies, and speeding discovery. They're also making their scientific research as widely available as possible, and incorporating local and community-driven science.

COLLABORATION AND CURIOSITY

There is a rich history of collaboration and technology exchange between astronomers and ocean scientists—even between our national agencies devoted to each type of science. With possible cuts to their operations, there's an enormous concern about the loss of data, of studies interrupted, particularly longitudinal studies, where we risk losing the work of generations of scientists. This is why Schmidt Sciences and our other science-focused philanthropies are working to find ways to preserve data and, wherever possible, ensure the continuation of critical work.

And while the challenges are many—from our changing planet, to the possibility of another pandemic, to securing funding for essential research, to the loss of accumulated scientific data—we know that science won't stop. Science offers us a constant source of awe and the hope for the answers that we, as a species, so doggedly seek: Why are we here? How did life begin, and how can it continue?


AI & Advanced Computing
Astrophysics & Space
Science Systems
Biosciences
Climate