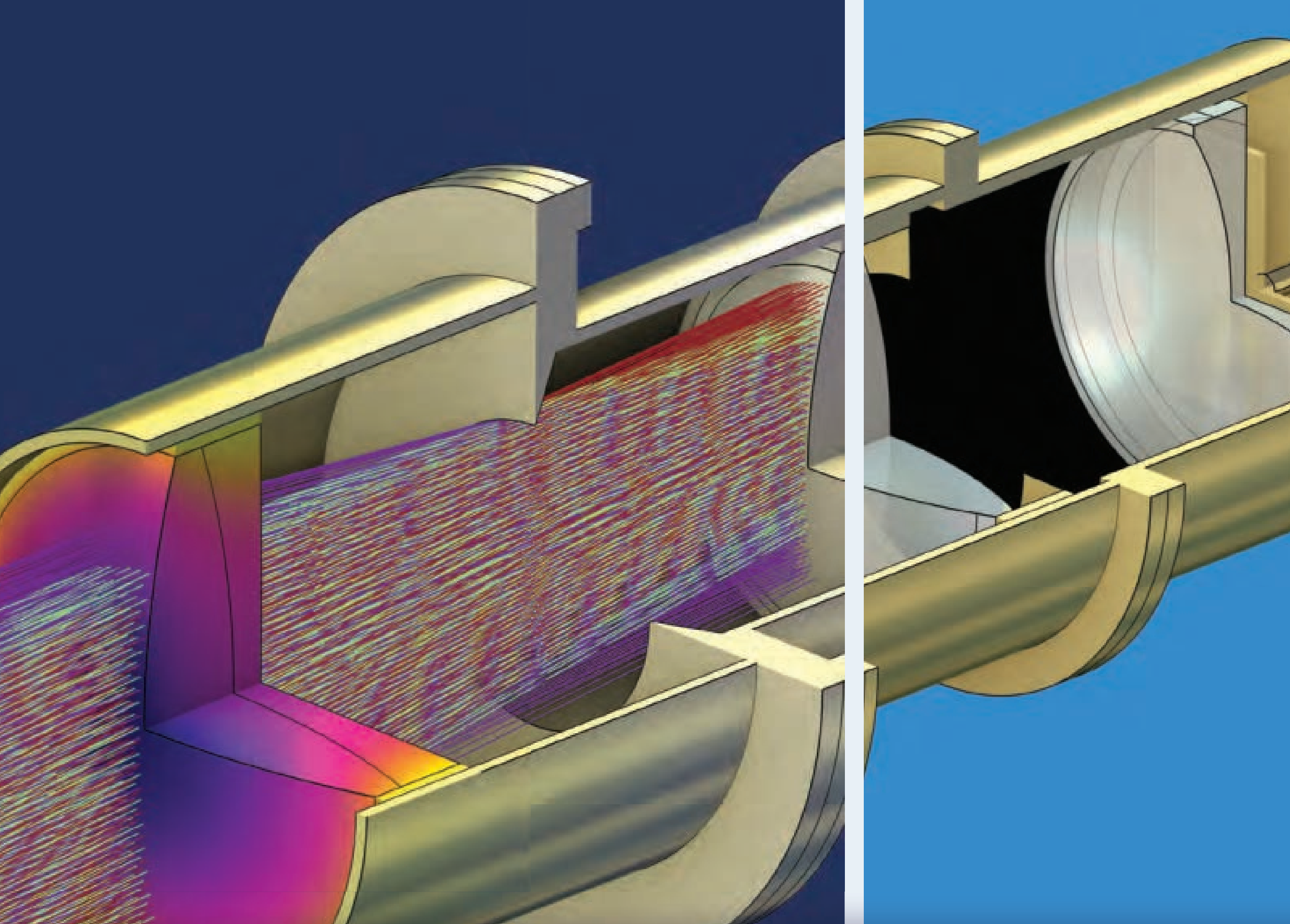


PHYSICS TODAY

February 2024 • volume 77, number 2

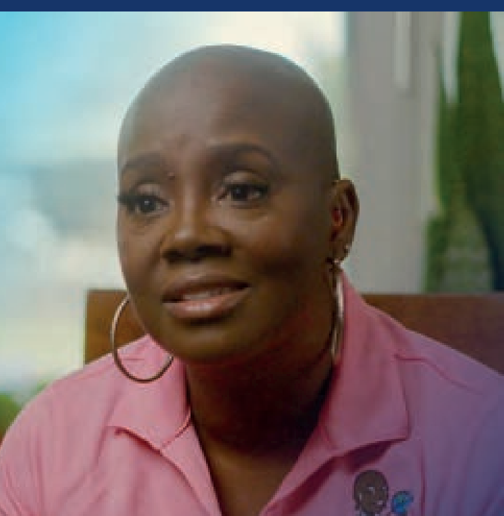
A publication of the American Institute of Physics

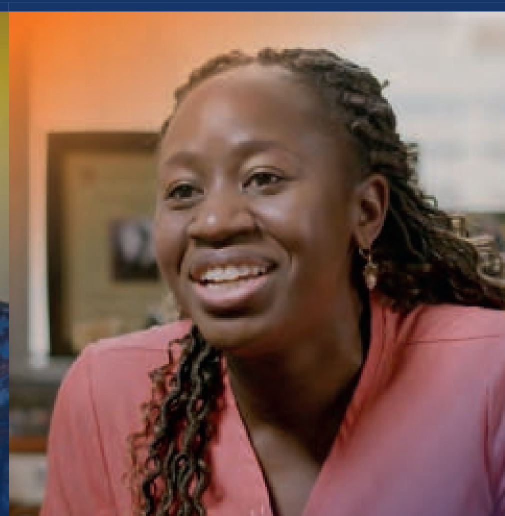
SETI and EXISTENTIAL PROJECTION

200 years of fracture

Astronomy in the classroom

Particle-physics road map





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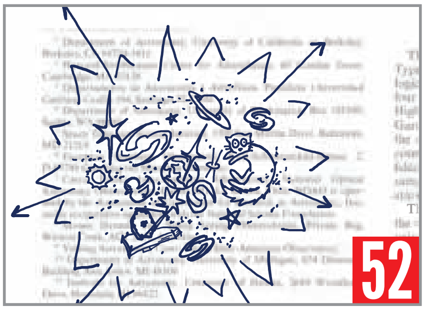

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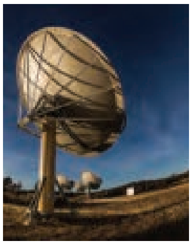

ON THE COVER: The search for extraterrestrial intelligence (SETI) relies on radio telescopes outfitted with extremely sensitive receivers. Early hunts used telescopes intended for conventional astronomical observations. The Allen Telescope Array, pictured here, is the first radio telescope designed specifically for SETI; it can probe several stellar regions and frequency bands at once. To learn about SETI's connections to artificial intelligence and our own future, see the article by Rebecca Charbonneau on **page 36**. (Image by Linus Platt via Getty Images.)

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Attracting H-1B workers

Last summer Canada invited 10 000 STEM workers from the US who hold H-1B visas to head north. The program, which quickly reached capacity, is designed to attract US-vetted STEM talent to Canadian employers while also imposing fewer restrictions than the US immigration system.
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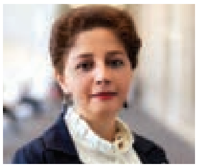

ENCIEH ERFANI

Displaced scholar

In September 2022, Iranian cosmologist Encieh Erfani spoke out against the government and resigned her position at an Iranian university. Out of the country at the time, she has not returned to Iran since. She talks to Physics Today about the challenges of finding a new professional and physical home.
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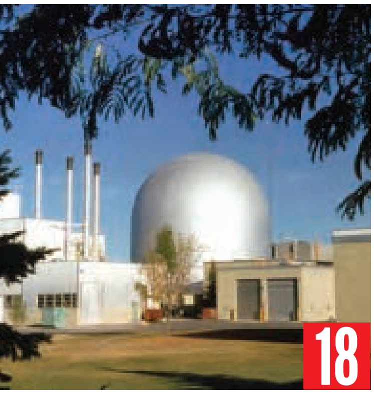

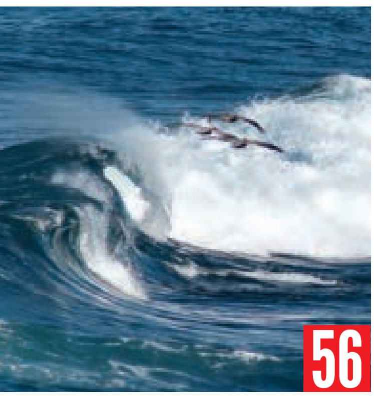

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Twisted liquid crystal

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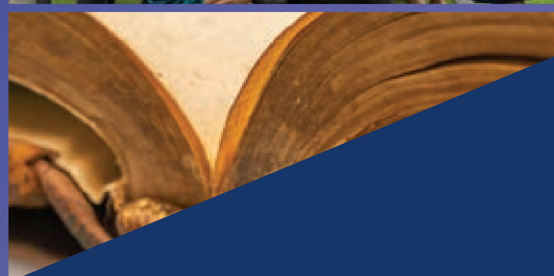

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Changing the clocks: Latitudes and attitudes

Next month the US (most of it, at least) and many other countries will adjust their clocks by one hour, a semiannual practice that is being challenged by people on either side of the Atlantic. In recent years we have looked into the interplay between the practice and physics, physiology, and sociology,[1–3] and we have found problems with the way opponents approach the issue. Some allege on the basis of poorly interpreted statistics (that nonetheless receive flashy headlines) that clock changing is harmful.[3] They seem to forget the discomforts that would arise at some latitudes from having a rigid clock and the way that clock adjustments provide a useful solution.

Human physiology suggests that the start of the day should be linked to sunrise. At low latitudes, the oscillation of sunrise times is small; therefore, clock changing is unnecessary. It is no surprise that a US senator from a southern state, Republican Marco Rubio from Florida, is the primary sponsor of a bill that would make daylight saving time permanent or that Brazil and most of Mexico recently abandoned clock changing. At high latitudes, on the other hand, the oscillation is too large for the practice to make much of an impact on the long summer and short winter daytimes.

But at midlatitudes, the situation is more complicated. At the latitude of New York City, for example, sunrise times oscillate by three hours over the course of the year. At those latitudes, it is hard to pick a start time that works for both seasons without changing the clocks: What works in the summer might be too dark and cold in the winter, and what works in the winter might be too bright and hot in the summer.

When people started advocating for shifting the clocks, they promised better alignment of the Sun and human schedules and more daylight for leisure time on summer evenings. And the practice delivered it. But it wasn't until World War I that Germany decided to implement clock changing, and eventually many other countries followed. Today the majority of Europeans and Americans, as well as people in several other countries, continue the practice.

People can make their clocks and schedules rigid, but the same cannot be said for sunrise times. The bottom line is simple: Changing the clocks helps people accommodate the otherwise extreme sunrise times in the winter and summer. The practice can be seen as a compromise.

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Multidimensional measurements

Our world is filled with measurements: Jill runs faster than Jane. Bill throws farther than Ed. Julia is a better mathematician than Josephine. Gary is a better economist than George. Notice that the first two are clearly linear measurements, achievable with a stopwatch and a measurement tape, respectively. The second two, on the other hand, involve a multitude of variables and require assessing their relative weight.

Multidimensional measures are well established in fields where quantification is difficult, such as poverty[1] and immigrant integration.[2] But some people in other fields, such as economics, have the conceit that they can measure things without the multidimensions. My goal here is to suggest a mathematical procedure for handling multidimensional measurements. My conclusion may not be profound, since some subjectivity is unavoidable, but it does illuminate the role that bias plays when people collapse a complex measurement into a linear one, as they so often do—for example, when voting or hiring faculty.

Consider, first, a linear quantity, such as the height one can reach when jumping. Given two choices, such as A and B, we can make a judgment, such as A is greater than B. Since A and B are scalars, we can order them, and there is no ambiguity about that order. They don't need to have predefined amplitude ranges, and they can even be irrational or transcendental. But they cannot be complex numbers or vectors, since those cannot be ordered. They may have uncertainties (error bars), but those can be defined and taken into account, essentially as probabilities for the sense of the inequality. My concern here lies in cases where the uncertainties are small enough to be unimportant.

Now consider instead the vectors $\mathbf{A}$ and $\mathbf{B}$. They belong to the same multidimensional space, which—for example, in the case of a faculty member up for tenure—could consist of a set of variables that are agreed by consensus to have relevance. We might agree on the parameters, and we might even agree on their relative importance, although that can be difficult. But we still need to agree on the rank order of $\mathbf{A}$ and $\mathbf{B}$.

To do so, we must construct scalars. A dot product is a scalar, and my (not unique, but plausible) suggestion is to think of the rank orderings as arising from dot products with normalized bias vectors, such as $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$. A large dot product arises when the bias is in a direction similar to the candidate vector's. We can then certainly have, for example, $\mathbf{A} \cdot \boldsymbol{\alpha} > \mathbf{B} \cdot \boldsymbol{\alpha}$, which is the ranking chosen by $\boldsymbol{\alpha}$, and still have $\mathbf{B} \cdot \boldsymbol{\beta} > \mathbf{A} \cdot \boldsymbol{\beta}$, which is the ranking chosen by $\boldsymbol{\beta}$. The two observers ($\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$) disagree on ranking, which is not uncommon. And our observers can be just as multidimensional as the attributes ($\mathbf{A}$ and $\mathbf{B}$) that they are ranking. In these equations, we're dealing only with scalars (dot products), and there is no ambiguity in the comparisons. Ambiguity is in the observers, not the data.

We could even have an "ideal" candidate $\mathbf{I}$ who is better than either $\mathbf{A}$ or $\mathbf{B}$ in the sense that $|\mathbf{I}| > |\mathbf{A}|$ and $|\mathbf{I}| > |\mathbf{B}|$ and yet preferred by neither—that is, $\mathbf{A} \cdot \boldsymbol{\alpha} > \mathbf{I} \cdot \boldsymbol{\alpha}$ and $\mathbf{B} \cdot \boldsymbol{\beta} > \mathbf{I} \cdot \boldsymbol{\beta}$. Of course, that presumes a consensus on relative merits of the attributes (implicit in the use of normalized vectors for $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$).

This template could be useful in job hiring, but that is not the only potential application. For example, the attributes of a football team can depend on whether the players are running on muddy or dry ground or whether they are at home or away.

In short, bias can be as important as attributes, and we should never think that we should try to understand the candidate (for example, $\mathbf{A}$) just by their attributes—it is about as important to understand the bias ($\boldsymbol{\alpha}$). Perhaps that is obvious, but a numerical example helps explain it and perhaps even quantify it. Left unresolved and unresolvable is the implicit need to agree on attributes, since without that, there can be no agreement on the vector space.

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Factors for assessing researchers

I enjoyed reading the Issues & Events piece "Global movement to reform researcher assessment gains traction" by Toni Feder (Physics Today, October 2023, page 22). I obtained my PhD in the mid 1990s, and since that time I have heard various degrees of dissatisfaction with faculty evaluation processes. It was nice to see the topic discussed in Physics Today.

While it is important to consider a wide range of contributions when assessing research faculty, I would like to speak out against including social impact and entrepreneurship among the factors considered. Research scientists and institutions ought to achieve their influence and status through their contributions to the altruistic endeavors of knowledge creation (research) and knowledge preservation (education).

Entrepreneurship is frequently antithetical to those goals and is instead aimed at the creation of profit-making enterprises. Likewise, "social impact," as it is normally construed, relates to influencing systems of power and the allocation of resources. While those endeavors are certainly important, they should be distinguished from the research goals of knowledge creation and preservation.

I like that Feder's piece discusses the role of objectively defined metrics versus subjectively defined expert judgment. Both kinds of evaluation are important. By working together and communicating in an open and respectful manner, we can build and sustain the kinds of institutions we want to work in.

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Elusive helium stars identified in archival data

After reinterpreting measurements for studying gamma-ray bursts, researchers found the progenitors of some supernovae.

FIGURE 1. A MILLION STARS in the Large Magellanic Cloud, 163 000 light-years away, were captured in thousands of UV images by NASA's *Neil Gehrels Swift Observatory*, which are overlaid here with visible light. The UV data and optical observations conclusively identify a population of massive helium stars stripped of their hydrogen by their binary companions. (Courtesy of NASA/Swift/S. Immler [Goddard]/ M. Siegel [Penn State].)

In the gravitational tug of war in a binary system, the hydrogen-rich outer layer of one star can sometimes be pulled away by its companion, leaving behind the compact, hot, and helium-rich core. Stripped helium stars should be abundant in the universe: Theory predicts that about a third of all massive stars should lose their hydrogen-rich outer layer and reach a range of 2–8 solar masses.

Once stripped stars collapse under their own gravitational forces, they'll generate hydrogen-poor supernovae because of their lack of an outer layer. But despite observing the supernovae and despite years of searching for midsize stripped helium stars, scientists had found only one. (In 2008, astronomers identified it as a 4-solar-mass candidate,[1] and its mass estimate was recently revised to the low end of the range, at 2 solar masses.[2])

Although stripped stars emit visible light, it's relatively faint and thus hard to detect. The companion in a binary system may outshine its stripped partner so much that astronomers may even mistake the system for one with only a single star.

Using a new UV-based method, Ylva Götberg (Institute of Science and Technology Austria), Maria Drout (University of Toronto), and their colleagues began an intensive search in 2016 for the elusive stars. They've now studied 25 of them, and the new analysis may help explain certain core-collapse supernovae.[3]

A serious search

Of the massive stars that explode to produce supernovae, about a third don't have much hydrogen, "which is actually a lot," says Drout, "if you're trying to figure out how a massive star, which should be mostly hydrogen, explodes without it." Astronomers have observed many helium-rich stars: massive so-called Wolf–Rayet stars larger than 8 solar masses and subdwarfs less than 2 solar masses. But only the elusive midsize stripped stars are consistent with hydrogen-poor supernovae.[4]

In 2016 Drout was making observations of hydrogen-poor supernovae as part of her PhD dissertation, which she defended that year. At a meeting of the International Astronomical Union held in New Zealand, she heard a talk by Götberg, a PhD student who was modeling the properties that stripped helium stars should theoretically have.

Götberg says, "I remember Maria saying something like, 'Are you serious about these stars? I think we can find them.'" The sales pitch was enough for Götberg, and the two began a collaboration. In the latter part of her PhD studies, Götberg focused on understanding the spectral characteristics of midsize stripped stars. Her simulations used mass, the suspected level of ionizing radiation emitted by such stars, and other assumptions to model their effective temperatures, surface gravities, and other properties.

Seeing in UV

A critical insight that Götberg learned from the modeling is that midsize stripped stars should emit and thus be detectable by UV light.[5] Even in binary systems with a bright companion in the visible spectrum, the UV flux from the dimmer stripped star should be substantial. Encouraged by that possibility, the researchers started looking for a UV survey that would give them the data they needed.

Observing the UV sky, however, is challenging. Earth's atmosphere absorbs a lot of UV light, which is good for people's health but not for identifying hot stars. Another big problem is dust, which obscures the UV emission from nearby massive stars in the Milky Way. The

Hubble Space Telescope captures UV light in high resolution and without impediment by Earth's atmosphere, but it looks at only relatively small patches of the sky at a time.

"There wasn't the perfect UV data set that was covering a large enough area of the sky but that also had crisp enough images of individual stars," says Drout. Between 2010 and 2013, however, NASA's *Neil Gehrels Swift Observatory* had collected thousands of UV images from two galaxies: the Large Magellanic Cloud (shown in figure 1) and the Small Magellanic Cloud. The *Swift* instruments weren't purposefully built for UV surveys of stars—they're designed to detect and study gamma-ray bursts—but during quiescent periods, the observatory collects measurements for many other studies, including capturing UV light at the scale and resolution necessary to hunt for hot helium stars.

One of the coauthors, Bethany Ludwig, had to develop a new method, as part of her PhD thesis, to measure the UV brightness of objects seen in the *Swift* images. The researchers then used Götberg's theoretical framework to filter the UV brightness of roughly 500 000 stars and identified hundreds of possible stripped stars.

"We found these candidates in the UV," says Drout, "but just showing that some star is bright in the UV doesn't say it's a stripped star. Really showing that that's what these are depended on getting the optical spectra and a lot of modeling."

First class

The researchers selected 25 candidates for further study, and Drout, Götberg, and Ludwig traveled to Chile. There they gathered spectroscopic data from visible light with the Las Campanas Observatory's Magellan telescopes. From the optical absorption measurements, they concluded that at least 16 of the 25 stars are stripped binaries.

Among other characteristics, the ones most likely to be stripped binaries had a lot of ionized helium and very little hydrogen, which indicates that the stars are extremely hot compared with subdwarfs and main-sequence stars of similar brightness. In addition, the spectral-line shapes were consistent with compact stars in the sought-after range of 2–8 solar masses. Figure 2 compares some of them with other classes of stars.

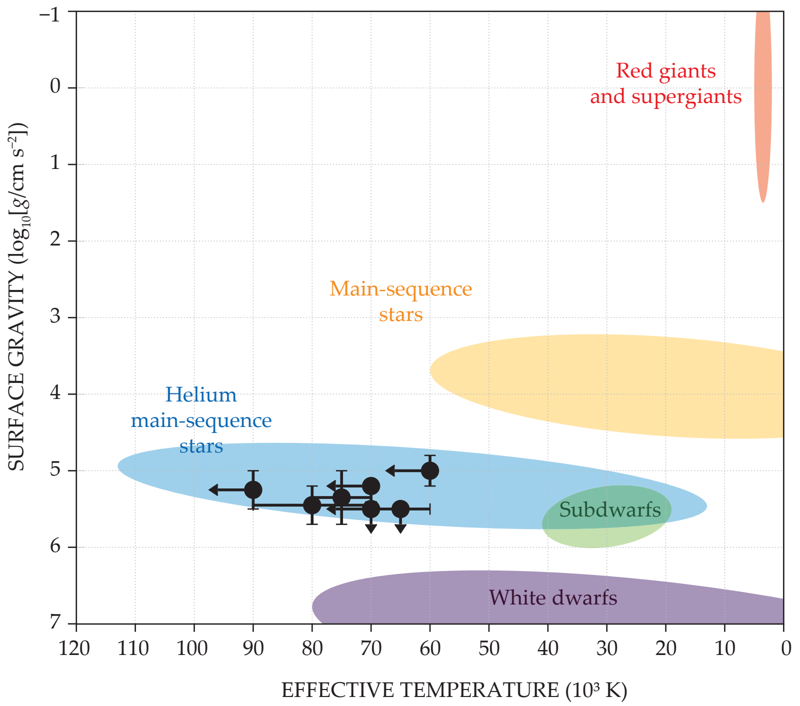

FIGURE 2. HELIUM-RICH STARS in the range of 2–8 solar masses weren't conclusively observed until recently, even though they're the likely progenitors of some common supernovae. The helium-rich stars most likely to be progenitors (black circles) have surface gravities g and effective temperatures consistent with theoretical predictions (blue oval) and are distinct from several other types of stars. (Adapted from ref. 3.)

The researchers grouped the 25 candidates into three types according to how much light is emitted by the stripped binary's companion. The first class, which they're most confident are supernova progenitors, have relatively dim, obscured companions. The second class has binary stars with roughly equal brightness. The third class has brighter companions, so the stripped stars are revealed only by their UV light, and those nine stars may not be stripped binaries.

The categories offer clues to the nature of the companion star and to the stripped star's stellar evolution. Some stripped stars are so bright that the companion's identity remains obscured—it could be, in those cases, a compact neutron star or even a black hole. The other stripped stars are a bit dimmer and may have a common main-sequence star for a companion.

Of particular interest to Drout is what's next in the life cycle. The stripped binaries could, for example, experience core collapse and explode as hydrogen-poor supernovae, producing neutron stars and black holes. Some of those supernovae could be sources of gravitational waves. Occasionally the newly born neutron star may already have a neutron star companion. If the two merged, rapid nuclear reactions would fuse the periodic table's heaviest elements.

"Now with these observations," says Jan Eldridge of the University of Auckland in New Zealand, who organized the conference where Drout and Götberg met, "we can really begin to study and understand helium stars and improve our understanding of the whole universe."

Alex Lopatka

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Atomic force microscopy gets a feel for electron spins

The microscopic mechanical measurements yield new insights into single molecules' chemical properties—and even their isotopic composition.

Though too small to see, atoms and molecules are not really invisible, and they're not beyond experimenters' reach. Researchers have imaged molecules on surfaces in stunning detail (see, for example, Physics Today, November 2012, page 14) and moved them around with exquisite precision (see Physics Today, January 2019, page 14), thanks to the twin techniques of scanning tunneling microscopy (STM) and atomic force microscopy (AFM). Both methods use a pointy probe to scan a surface, as shown in figure 1, the former by passing a current of electrons through the surface and the latter by feeling it like a tiny finger.

But the toolbox of single-molecule techniques is far from complete, and the more answers researchers uncover, the more questions they come up with. How, for example, do a molecule's physical and chemical properties depend on its specific microenvironment? And when two molecules collide and react—a shake-up that often involves the rearrangement of many identical atoms—which atoms go where?

To help answer such questions, Lisanne Sellies of the University of Regensburg in Germany, her PhD adviser Jascha Repp, and their colleagues have unveiled an unexpected new technique: using AFM to make electron-spin-resonance (ESR) measurements of single molecules.[1] ESR, a cousin to the more familiar nuclear magnetic resonance, probes energy differences between electron spin states to yield information about atomic and molecular properties.

At first glance, the spin states measured by ESR would seem to have little to do with the mechanical force measurements of AFM. But with a clever and serendipitous chain of discoveries, the Regensburg researchers made the connection.

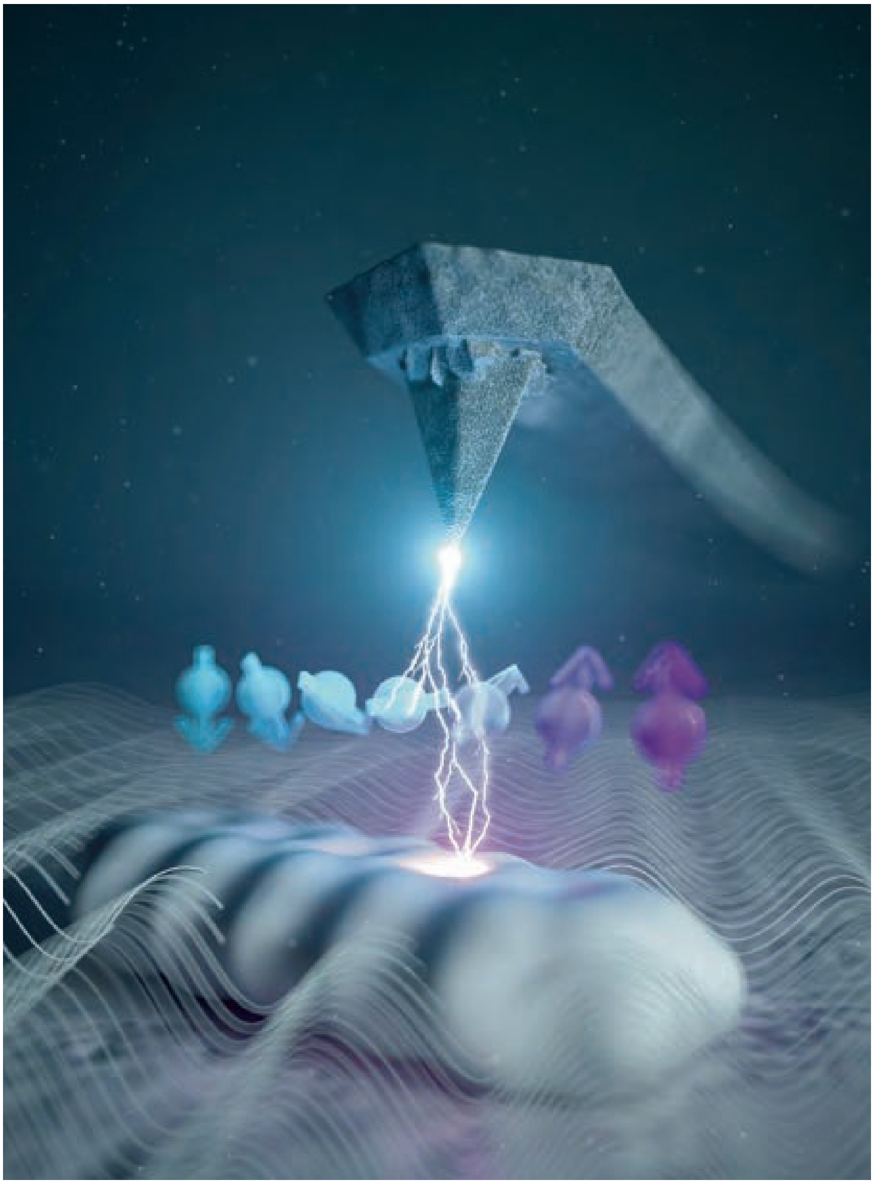

FIGURE 1. THIS ARTIST'S IMPRESSION shows an atomic force microscopy tip probing the electron spins of a pentacene molecule—a chain of five fused carbon rings—on a surface. (Image © Eugenio Vázquez.)

A light touch

Typically, ESR is a bulk measurement performed on billions of molecules or more. The large sample is good for building up signals, but it obscures molecule-to-molecule variations. Single-molecule ESR measurements, based on molecular fluorescence, date back to the 1990s.[2] But even though those experiments, led by William Moerner and Michel Orrit, picked up single-molecule ESR signals, they lacked molecular resolution: They were unable to gather any other information about the molecule, its location, or its environment.

True atomic-scale resolution in ESR came in 2015, when Andreas Heinrich and colleagues demonstrated an STM-based ESR measurement of single atoms on a surface.[3] (They later extended the technique to molecules on surfaces.[4]) With the ability to observe and manipulate atoms and molecules and measure their spin states, all with a single pointy probe, ESR–STM is a powerful technique.

But it's not ideal. To measure a single electronic spin state, ESR–STM floods the atom or molecule with a current of millions of electrons, which disrupts the spin's coherence and makes the measurement harder. Coherence is especially important in studies of molecules' quantum properties—including their potential use in a quantum computer.

AFM-based ESR would be a gentler approach, but it wasn't clear how it would be possible. An electron spin can exert forces on an AFM tip through the dipole–dipole interaction or the exchange interaction, which is based on the Pauli exclusion principle: Electrons with the same spin orientation can't be in the same place at the same time. But neither of those forces has yet yielded an atomic-scale ESR measurement.

Triplet of triplets

Repp and his group are experts in AFM, not ESR, and they didn't set out to develop a new method for single-molecule ESR. They came to ESR indirectly, after some work they did a few years ago on using AFM to measure molecules' triplet-state lifetimes.[5]

Most molecules in their ground states are spin singlets: Every electron has an opposite-spin partner, and the net spin is zero. Exciting a molecule to a higher energy can break up one of those pairs to create a spin triplet. Triplet states are important for their chemical reactivity, and because spontaneous relaxation from a triplet to a singlet is quantum mechanically forbidden, they tend to be long lived. But certain nearby molecules can quench the triplet state, or accelerate its decay. It was such triplet quenching that Repp and colleagues wanted to study.

Although an AFM probe doesn't normally carry a current, it can remove single electrons from a molecule and place them into higher-energy states. Repp and colleagues used that catch-and-release process to prepare a molecule in a triplet state, waited a few microseconds, and then plucked an electron back out of the molecule only if it was still in the excited state. From there, a standard AFM measurement easily determined whether the molecule was charged. By repeating the process a few thousand times, the researchers built a picture of a triplet state's decay curve, and they could see whether the triplet state is quenched by various molecules placed in the vicinity.

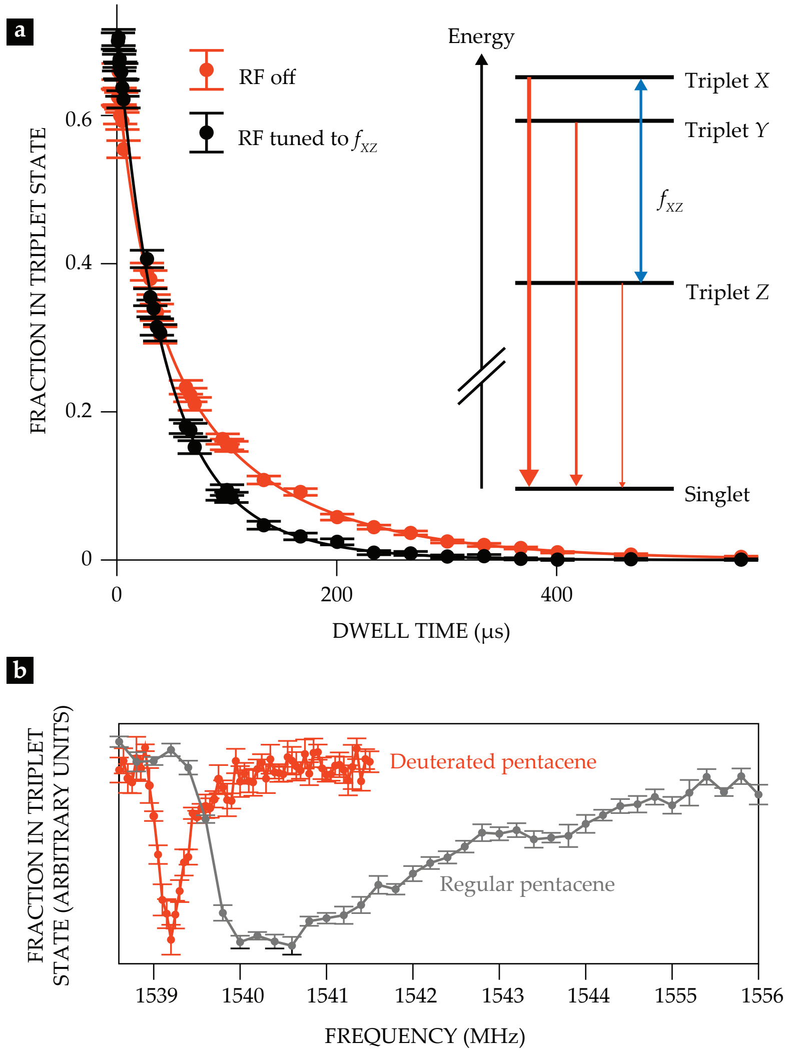

FIGURE 2. SINGLE-MOLECULE SPIN RESONANCE. (a) The three substates of pentacene's triplet state all decay to the ground state at different rates, as indicated by the vertical red arrows in the inset. Tuning an RF pulse to a spin resonance f_{xz} pumps molecules from a longer-lived state to a shorter-lived one and speeds the triplet's overall decay, as shown in the main plot. **(b)** By sweeping the RF frequency and tracking the fraction of the time the molecule is in the triplet state after a fixed dwell time, researchers can plot the molecule's full electron-spin-resonance spectrum. The spectra can distinguish between molecules with different isotopic compositions. (Adapted from ref. 1.)

For their proof-of-principle experiment, the Regensburg researchers studied the triplet lifetime in pentacene, a chain of five fused benzene rings, which is a common test molecule in surface studies. Because pentacene is anisotropic in shape, its triplet state is really three distinct states, each with a slightly different energy and a slightly different decay constant, as shown in the inset in figure 2a. Those differences turned out to be key to making a single-molecule ESR measurement—just as they'd been key to the fluorescence-based measurements of the 1990s.

In their experiments decades ago, Moerner, Orrit, and their groups monitored the lifetime of triplet pentacene by tracking how long after excitation the molecule took to fluoresce. At the same time, they applied an RF pulse in an attempt to shuttle the molecule between two of its triplet states. When the pulse hit the right frequency to pump the molecule from a longer-lived triplet state into a shorter-lived one, the apparent lifetime abruptly changed, and the researchers knew they were on resonance.

Inspired by those experiments, Repp, Sellies, and colleagues did the same thing. And as shown in figure 2a, it worked: When the RF pulse frequency matched a pentacene spin resonance, the triplet state decayed noticeably faster than it otherwise would have. By sweeping the RF frequency, then, the researchers could collect a full spin-resonance spectrum of a single molecule.

Tracking atoms

So what is an AFM-based ESR technique good for? Although the full potential has yet to be realized, the Regensburg researchers have some ideas.

For one possibility, they've shown that they can coherently manipulate the triplet-state spins for up to tens of microseconds, which is more than an order of magnitude longer than ESR–STM can usually achieve. The longer coherence time—and the fact that the coherence isn't so severely disrupted by the measurement technique itself—opens the door to detailed experiments to investigate how spin coherence is affected by other atoms and molecules in the vicinity.

For another, they've begun to explore how the technique can distinguish between forms of the same molecule with different isotopic compositions. Figure 2b, for example, shows the differing ESR spectra of a pentacene molecule whose hydrogen atoms are the usual ^{1}H isotope (gray) and one in which they're all replaced by deuterium (red). Isotopic information is all but invisible to ordinary AFM, which can barely even see hydrogen atoms, let alone distinguish their isotopes. But the spin-½ ^{1}H nuclei couple to and broaden the electron spin resonance in ways that the spin-1 deuterons don't.

The researchers can even distinguish a fully deuterated pentacene molecule from one with just one ^{1}H atom. They haven't yet fully explored how to tell which site on the molecule the lone ^{1}H atom occupies, but if they can develop that capability, it would open up the possibility of atom-by-atom tracking of chemical reactions. Researchers could prepare two molecules with isotopic labels at specific sites, prompt them to react, and see where the various isotopes end up.

Johanna Miller

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Panel recommends road map for US particle physics

The community welcomes the recommendations, recognizing them as fair and balanced within a constrained budget.

The High-Luminosity Large Hadron Collider. The Deep Underground Neutrino Experiment (DUNE). The Vera C. Rubin Observatory. Completing and supporting such ongoing projects is the highest priority in the recommendations for particle physics for the next decade and beyond, as laid out in *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*. The report was released on 7 December by the US Particle Physics Project Prioritization Panel (P5).

Among new large projects, the panel taps the Cosmic Microwave Background Stage 4 experiment at the South Pole and Chile as the top priority. It sets paths for supporting a Higgs factory, a next-generation particle collider, dark-matter searches, and an upgrade to DUNE. It emphasizes maintaining balance in terms of the science addressed, the size and time scales of projects, and the locations of experiments in and outside the US. It also stresses the importance of experimental and theoretical research and workforce training. (See the chart on page 21.)

The Department of Energy and NSF charged the panel with formulating strategies given two budget scenarios. Both start from the 2023 annual funding for particle physics from DOE of nearly $1.2 billion. The better scenario involves a boost over five years from the CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act and an annual increase by a projected inflation rate of 3%. By 2033, funding would be $1.85 billion. The less favorable one supposes funding increases at just 2% a year, reaching $1.45 billion by the end of the period. Funding from NSF for particle physics is much smaller and comes from multiple offices; it is omitted from the scenarios.

A broad portfolio

Hitoshi Murayama, a theoretical physicist at the University of California, Berkeley, chaired the 32-member P5. The biggest challenge, he says, was winnowing the huge number of ideas generated by the community (see PHYSICS TODAY, October 2022, page 22). Despite many ideas having been left on the back burner to fit into constrained budgets, the community has widely embraced the panel's recommendations. As of mid January, more than 3100 particles physicists, mostly from the US and across all career stages and subfields, had signed a letter in support of the P5 road map.

In the past, the sought-after physics was known, says Julia Gonski, a collider physicist who last fall started a tenure-track-equivalent position at SLAC. "There had to be a Higgs particle. Now it's the Wild West. Instead of looking in depth, we need a broad search. We have to look for anything that could be a deviation from the standard model. Hints will become a compass to follow." That uncertainty represents a cultural shift in particle

GEOFF CHEN

A COSMIC MICROWAVE BACKGROUND EXPERIMENT got top marks from the latest Particle Physics Project Prioritization Panel. The Stage-4 CMB would consist of one 5-meter and nine 0.56-meter telescopes at the South Pole, near the existing CMB experiments (shown here) and two 6-meter telescopes in Chile's Atacama Desert.

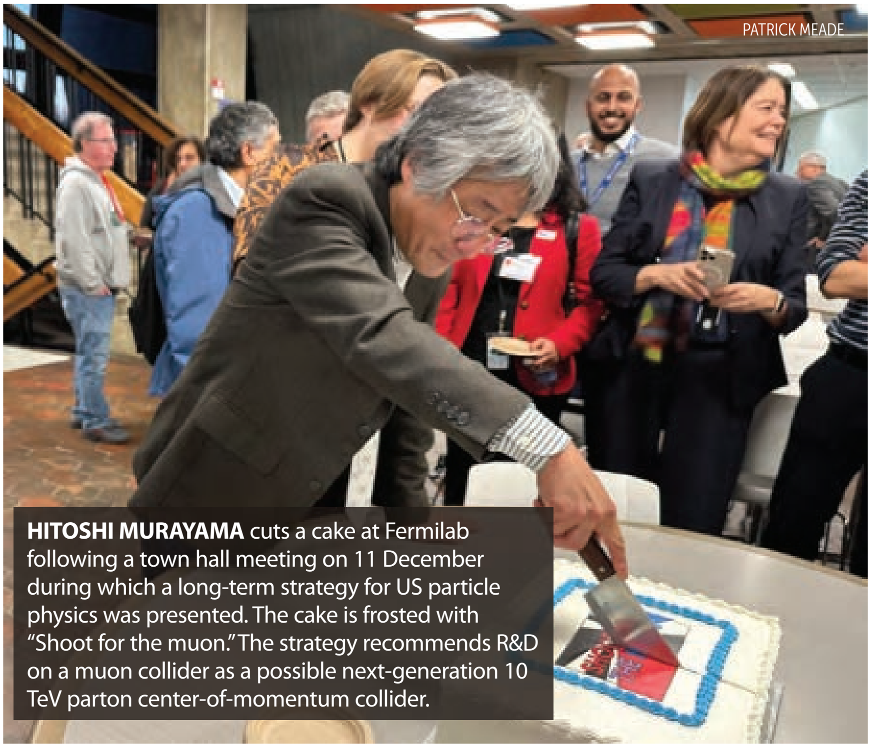
physics, she says. "P5 delivered a nice strategy that should be very exciting to the early-career community."

The major projects, defined as having a price tag that exceeds $250 million, are the only five that the panel recommended in ranked order (see table on page 20). Among the medium-scale ($50 million–$250 million) projects P5 recommends are contributions to upgrades to US and international experiments that study cosmic evolution, search for dark matter, and detect particles and phenomena from hints remaining from quantum fluctuations in the early universe.

The panel also recommends that DOE create a program to fund small projects, called Advancing Science and Technology Through Agile Experiments. The program should be funded at $35 million a year and put out regular calls for small projects that can see results in a few years, the report says. The aim is to allow for creativity, exploration, and training.

Funding for theoretical research at universities should be increased by about $15 million a year—over the current $55 million to $60 million—to bring such support back to 2010 levels, the report says. That and increases in other areas of research are intended to pave the way for future innovation and ensure international competitiveness.

"Research is where creativity shines, where you take a gamble and allow people to be creative and find things that might be big in the future," says P5 member Abigail Vieregg, a cosmologist at the University of Chicago. "In-



PATRICK MEADE

HITOSHI MURAYAMA cuts a cake at Fermilab following a town hall meeting on 11 December during which a long-term strategy for US particle physics was presented. The cake is frosted with "Shoot for the muon." The strategy recommends R&D on a muon collider as a possible next-generation 10 TeV parton center-of-momentum collider.

vesting in research is critically important. It's not just about building big flagship projects."

Overall, the total projected particle-physics budget scenario is broken down into roughly a third each for research, projects, and operations.

The loudest pushback that P5 members have received regards five experiments that would piggyback on the Large Hadron Collider to explore neutrinos and dark matter. "I am very disappointed," says Shih-Chieh Hsu, an experimental particle physicist at the University of Washington. "Although I support the report, I had hoped that P5 would be more friendly to cultivating such a facility." The report suggests that if CERN does proceed with the required civil engineering, the experiments could apply individually for funding under the small-projects portfolio it recommends.

Major new projects, from highest to lowest priority

More favorable budget scenario	Less favorable budget scenario
Cosmic Microwave Background Stage 4	
The CMB-S4 would study light from the beginning of the universe to search for signatures of primordial gravitational waves, probe dark matter and dark energy, and more. It would consist of one 5-meter and nine 0.56-meter telescopes at the South Pole and two 6-meter telescopes in Chile's Atacama Desert.	No reduction in scope.
Deep Underground Neutrino Experiment, phase 2	
The upgrade would comprise an early enhancement of the facility's accelerator at Fermilab, a third underground detector module 1300 kilometers away at the Sanford Underground Research Facility (SURF), and an upgrade to the facility's near-detector complex. The main goal for phase 2 is to seek neutrino–antineutrino asymmetry.	Proceed with the third far detector; defer upgrades to the accelerator and near detector.
US investment in an off-shore, international Higgs factory	
The candidates are a 97-kilometer circumference electron–positron collider at CERN and the International Linear Collider, a mature design that Japan has been considering hosting for years.	Reduce and delay contributions.
Generation 3 dark-matter experiment	
The experiment would search for dark matter—specifically weakly interacting massive particles.	No SURF expansion or US-based G3 dark-matter experiment; reduce participation in experiment outside the US.
IceCube-Gen2	
The expansion would improve the sensitivity of NSF's Antarctic neutrino observatory 10-fold by increasing its volume and number of sensors. Among other aims, IceCube-Gen2 would identify high-energy astrophysical neutrino sources and determine their flavor ratios. It would look for neutrino signatures beyond the standard model.	No reduction in scope.

Based on information in *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*.

Shooting for the muon

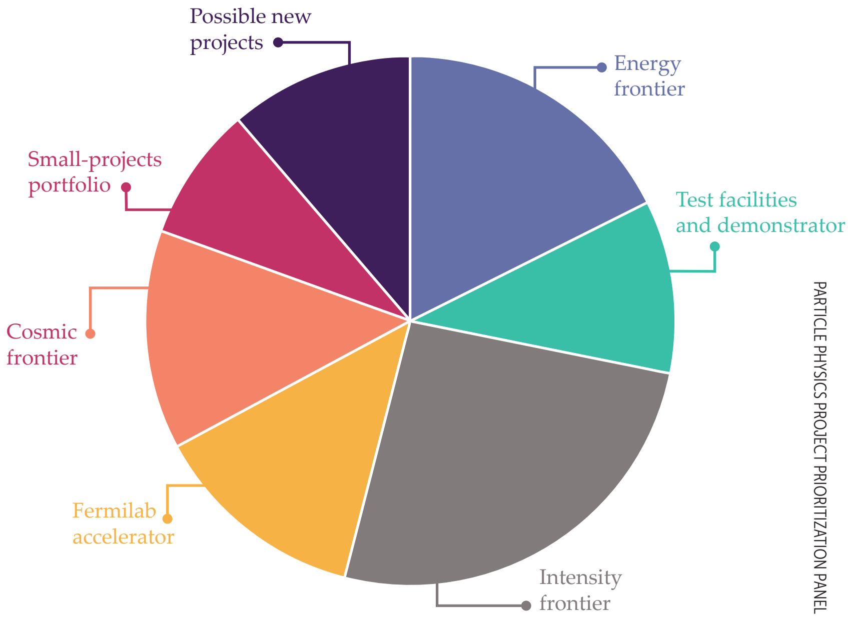
The report recommends "vigorous R&D toward a cost effective" 10 TeV parton center-of-momentum (pCM) collider. Such a collider would explore energies roughly an order of magnitude higher than are accessible with the Large Hadron Collider. It could be based on protons or muons, or on wakefield or other new accelerator technologies that would make linear colliders shorter and cheaper.

US particle physicists are especially excited about the possibility of a muon collider. As fundamental particles, muons would need to be accelerated to 10 TeV to achieve 10 TeV pCM, rather than the 100 TeV that a proton collider would require. That means that the facility could be smaller and could fit on the Fermilab campus. "Hosting the next major collider on US soil would be fantastic," says Patrick Meade, a theoretical physicist at Stony Brook University.

The idea for a muon collider came up short in the previous P5 report, from 2014, because of the challenges. Muons have a lifetime of just 2.2 microseconds and would have to be cooled, bundled, and collided within that window.

But progress in technology has revived interest in a muon collider. For example, the strong superconducting magnets developed for the ITER fusion experiment didn't exist a decade ago, and a similar technology could be used to collect muons, says Meade. "All the pieces of technology exist as independent components," he says. "We need to bring them together to make a demonstrator and show that a muon collider is possible."

Because muons are heavier than electrons, they have the advantage of producing less synchrotron radiation, and as they are accelerated to higher energies, they live longer because of time dilation. "Muons give you the best of



PARTICLE PHYSICS PROJECT PRIORITIZATION PANEL

SCIENTIFIC BALANCE AND DIVERSITY are among the goals of the latest long-term strategy for US particle physics. The chart shows a snapshot of investment areas for 2033 if the strategy's recommendations are implemented.

both worlds: high energies and precision simultaneously," says Meade. Many unknowns remain, but a muon collider would likely cost in the neighborhood of $10 billion, he says.

CERN and China are considering 100 TeV colliders. They would first build an electron–positron collider some 100 kilometers in circumference, and then upgrade it to collide protons. (See "China plans a Higgs factory," PHYSICS TODAY online, 17 December 2018, and "CERN considers a 100 TeV circular hadron collider," PHYSICS TODAY online, 5 February 2019.) "It's too early to get behind any single machine," says SLAC's Gonski. If the Future Circular Collider at CERN goes forward, it would be ready for data taking in 2045 in its initial electron–positron incarnation, and in 2070 as a proton collider. It would be the last iteration of going bigger to get to higher energies, says Gonski. "We won't build a 1000-kilometer ring next time. For long-term success, we need to get to smaller footprints."

The P5 report sets a goal of being ready to build test and demonstrator facilities for 10 TeV pCMs within 10 years. It also recommends convening task forces to evaluate the options and specify next steps once more information is available.

Leadership loss

If funding turns out to be closer to the less favorable scenario, some aspects of the DUNE upgrade and many other projects would be curtailed or delayed. The recommendation to dig a new cavern for a third-generation dark-matter experiment at the Sanford Underground Research Facility in South Dakota would be replaced with contributing to an experiment outside the US (see table). Theory funding would be increased less, and support for small projects through the Advanced Science and Technology Through Agile Experiments program, as well as computing, instrumentation, and collider R&D, would be slashed.

The lower budget scenario "represents erosion," says Murayama. "It would result in the US losing leadership in many areas." It would also cast doubt on the US as a reliable partner in international projects, he says. Now he and colleagues are busy briefing policymakers and government agencies to muster support for funding their field.

Toni Feder

US takes another look at recycling nuclear fuel

Proponents see a reduction in the need for uranium mining and more efficient, cheaper reactors. Opponents see a risk of proliferation.

As the Biden administration seeks to triple the nation's nuclear energy capacity in response to climate change, it is edging closer to lifting a more than four-decade-long moratorium that the US has observed on the recovery of plutonium from spent nuclear fuel. Ending the prohibition is critical to the plans of some advanced reactor developers, but it would be a major change in US nonproliferation policy, which opposes separating plutonium that could potentially be stolen or diverted to construct a nuclear explosive device. Current policy also recognizes that reprocessing by the US could encourage other nations with nuclear power to follow suit.

Department of Energy officials say the moratorium on commercial reprocessing will remain in place for now. But the Biden administration has shown a receptiveness to reprocessing that contrasts sharply with his Democratic predecessors, dating to Jimmy Carter. "The Biden–Harris administration and DOE recognize the importance of developing practical uses for America's used nuclear fuel," energy secretary Jennifer Granholm stated in October 2022. "Recycling nuclear waste for clean energy generation can significantly reduce the amount of spent fuel at nuclear sites and increase economic stability for the communities leading this important work."

"With many advanced reactor designs that could use spent nuclear fuel coming closer to reality, DOE is assessing reprocessing and recycling technologies with more urgency," stated Kathryn Huff, DOE assistant secretary for nuclear energy. In written responses to questions, Huff said the agency will continue R&D on reprocessing approaches "to assess options as technologies and economics evolve."

A spokesperson for the National Nuclear Security Administration, the semiautonomous agency that monitors DOE's nonproliferation policy, said it supports "limited, responsible" R&D on reprocess-

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LA HAGUE, FRANCE, is the site of one of two operational commercial reprocessing plants in the world. Russia's state-owned Rosatom also offers commercial reprocessing services. The UK's Sellafield reprocessing plant closed in 2022.

ing to evaluate options. "We also recognize that US industry and other countries are pushing forward on nuclear fuel recycling concepts whether we like it or not, and not always with the same commitment to nonproliferation that we have." The spokesperson added that "the jury is still out" on whether reprocessing technologies can be developed that will adequately address proliferation concerns.

A 2023 report by the National Academies of Sciences, Engineering, and Medicine recommends that the once-through nuclear fuel cycle be continued "for the foreseeable future." It also calls for "fundamental studies" on reprocessing to be maintained.

The US and 21 other nations pledged to triple their nuclear energy outputs by 2050 during December's United Nations Conference of the Parties climate change conference in Dubai. DOE is placing its bets on advanced nuclear technologies, which it says promise to be cheaper, quicker to build, and safer than today's hulking light-water reactors (LWRs). Many of those advanced technologies would benefit from reprocessing, and several companies include reprocessing as integral to their business plans.

Plutonium stockpiles

The International Atomic Energy Agency says that as little as 8 kg of plutonium could produce a crude explosive device; more sophisticated actors, it says, might require just 3.5 kg.

Reprocessing by other nations has produced commercial stockpiles of plutonium totaling 410 metric tons (t) in storage at locations in Russia, France, Japan, and the UK, most of which has no clear disposition path, according to the International Panel on Fissile Materials. The UK alone has accumulated 116 t of civilian plutonium. Russia and France continue commercial reprocessing today. In 1997 Japan began construction of a reprocessing plant that has yet to operate.

To be suitable for LWRs, the separated plutonium must be mixed with depleted uranium to form mixed-oxide (MOX) fuel. MOX fuels are used for roughly 10% of France's nuclear energy production, says Frank von Hippel, an emeritus professor of physics at Princeton University whose research focuses on nonproliferation issues. But Électricité de France, which operates all five of the UK's power reactors and is building another there, declined to buy MOX fuel from Britain's Sellafield reprocessing facility, opting for the once-through fuel cycle instead, he notes. Previous Sellafield customers in Belgium, the Netherlands, and Switzerland all abandoned MOX fuel. Lacking any customers, Sellafield was shut down in 2022.

"Reprocessing as it exists today is certainly not competitive with a once-through cycle," says Ross Matzkin-Bridger, senior director for nuclear materials security at the Nuclear Threat Initiative. "I have not seen any kind of analysis that would indicate that reprocessing becomes cost-competitive or cost-advantageous for advanced reactor technologies."

Huff said reprocessing can conserve uranium, lessen the environmental impacts of mining, and lower US dependence on uranium imports. Reprocessing all the nation's spent fuel could reduce the need for mined uranium by a factor of 100 or greater, she said.

Opponents of reprocessing say that uranium will remain plentiful for the foreseeable future. "Reprocessing started because of a belief that uranium was relatively scarce and expensive and that as nuclear power grew, uranium would become more expensive and it would pay to breed new fissile fuel," says Steve Fetter, dean of the graduate school at the University of Maryland, who is active in nonproliferation issues. "That hasn't been the case." Even at today's relatively high uranium price, he says, "we are far below the level that would make reprocessing economically attractive."

Fast reactors

Driving DOE's support for reprocessing R&D is the hope that many of the advanced reactor types, so-called fast reactors, will catch on commercially. Of the 60 or so advanced reactor designs under development globally, 25 are fast reactors, according to the International Atomic Energy Agency. The Bill Gates–backed Natrium reactor, which is to receive a $2 billion subsidy from DOE, is a liquid-sodium-cooled fast reactor. (See Physics Today, November 2021, page 25.)

Unlike LWRs, which slow neutrons to make them more likely to be captured by the fissile ^{235}U isotope, fast reactors produce high-energy neutrons. Fast reactors breed plutonium from ^{238}U, which accounts for about 95% of the content of spent LWR fuel. Some fast reactors can

THE EXPERIMENTAL BREEDER REACTOR-II at Idaho National Laboratory operated from 1964 to 1994. The sodium-cooled fast test reactor inspired Oklo's planned Aurora fast reactor, which the company plans to commission at the Idaho laboratory by 2027. Aurora will get its initial fuel load from the reprocessed spent fuel of the now-decommissioned reactor.

produce more plutonium than they fission. They also can transmute the other actinides in spent fuel, such as neptunium and americium, into short-lived fission products.

Fast reactors require fuel that's more enriched in ^{235}U than the 3–5% typical for LWRs. That so-called high-assay low-enriched uranium (HALEU) is enriched up to 19.75% in ^{235}U. (See "DOE plans bomb-grade uranium fuel for Idaho reactor," Physics Today online, 17 May 2023.)

DOE plans to provide fast-reactor developers with initial loadings of HALEU fuel. It will accomplish that by diluting some of the department's surplus highly enriched uranium, which is mostly 93% ^{235}U. On 9 January the agency issued a solicitation for industry to supply HALEU, but it will take many years to gear up commercial enrichment providers. Apart from small amounts produced by Centrus in Ohio, Russia has the only commercial provider of HALEU. Since fast reactors can fission and breed reprocessed plutonium, they could cut the need for HALEU in half, says Huff.

Fast reactors and reprocessing could reduce by 90% the volume of nuclear waste that will need to be stored in a geological repository for tens of thousands of years, according to Huff. It could cut by a similar fraction the amount of long-term radiation from the spent fuel by transmuting the actinides. But a 1996 report from the National Research Council concluded that the rate at which actinides can be fissioned is so slow that it could take hundreds or even thousands of years of continuous reprocessing and recycling to make a meaningful reduction in the total amount of waste.

"DOE is in the difficult position of trying to justify its call for a huge expansion of nuclear power when the US is unable to move forward with a program to dispose of the nuclear waste that has already been generated," says Edwin Lyman, director of nuclear power safety at the Union of Concerned Scientists.

Matzkin-Bridger notes that reprocessing also produces a much larger volume of low-level waste—items that are contaminated with radioactive material or that become radioactive through exposure to neutron radiation—and creates several new waste streams. "Reprocessing is not an answer to the spent-fuel challenge," he says.

A closed fuel cycle

Since the initial 1977 ban, US reprocessing policy has seesawed through successive administrations. Republican administrations have been mostly supportive of reprocessing, while Democratic presidents have favored continuation of the prohibition. Ronald Reagan removed the ban, but without government subsidies, there was no commercial interest, and US nuclear utilities opted for a spent-fuel repository that remains to be built. Bill Clinton reinstituted the moratorium, and George W. Bush proposed the Global Nuclear Energy Partnership, a multinational program that included building fast reactors and reprocessing plants in the US, Russia, and other nuclear weapons states. Congress declined to fund the program, and Barack Obama reinstituted the reprocessing ban shortly after entering office.

Reprocessing is integral to the business plans of some advanced-reactor developers. One, Oklo, plans to build a liquid-metal-cooled fast reactor it calls Aurora at the Idaho National Laboratory site by 2027. The lab has agreed to provide the Santa Clara, California–based company with Aurora's initial fuel load, supplied from the reprocessed waste from a decommissioned experimental fast reactor at the lab site. Oklo is preparing to reapply for a license to build and operate Aurora after the Nuclear Regulatory Commission turned down its initial application in January 2022.

"Our business model involves setting up our own fuel cycle to supply reactors," an Oklo spokesperson said in written responses to questions. "By efficiently utilizing recycled fuel, our advanced fuel recycling process contributes to reducing and ultimately eliminating plutonium." The spokesperson added that the use of recycled fuel for Aurora can be done safely and economically within the existing US policy framework.

Oklo has received at least $15 million from DOE to develop its reprocessing technology. That includes an October 2022 award of $4 million from one of two programs of DOE's Advanced Research Projects Agency–Energy (ARPA–E) that support reprocessing R&D and other spent-fuel management technologies. Initiated during the current administration, the ARPA–E programs have dispensed a total of $74 million to 19 companies, universities, and national laboratories to date.

The technology used in existing commercial reprocessing plants is an aqueous method known as plutonium–uranium extraction (PUREX). The US developed PUREX during the Cold War nuclear weapons buildup. Even proponents of reprocessing acknowledge that PUREX presents an unacceptable proliferation risk. India's first atomic test in 1974 was with plutonium clandestinely extracted using the PUREX process. The US provided technical assistance to build that supposedly civilian facility.

Most alternative reprocessing technologies in development today are based on electrometallurgical separation techniques, which aim to increase proliferation resistance by keeping other waste elements mixed with plutonium. That's the approach being followed by Oklo. But other technologies are also being explored. TerraPower, developer of the Natrium fast reactor, has received $8.6 million, the largest grant from one of the ARPA–E programs, to mature a process that exploits the volatility of chloride salts at high temperatures to recover uranium from spent fuel.

Shine Technologies, a Wisconsin company, proposes to build a standalone commercial reprocessing facility in the state to treat spent fuel from nuclear utilities. CEO Greg Piefer says the plant will likely incorporate an aqueous separation process. "It's not just about recycling plutonium because there's a tremendous amount of other valuable isotopes in the waste stream that are beneficial to humans," he says. Separating those, he continues, "is much more easily done with an aqueous stream."

Ross Radel, Shine's chief technology officer, says its separated product will be a 5:1 uranium–plutonium mixture, similar to MOX fuel.

Opponents of reprocessing argue that alternative separation processes would only delay the time required to render the plutonium usable for a weapon. A nation aspiring to produce nuclear weapons could further purify plutonium by tweaking the newly developed technologies, notes Fetter.

One 2009 evaluation of alternative reprocessing technologies by researchers from six national laboratories found only a modest improvement in reducing proliferation risk over existing PUREX technologies, and those modest improvements applied primarily to subnational groups, such as terrorists.

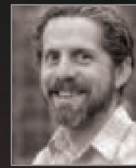
Two attempts at commercial reprocessing in the US failed. A plant in West Valley, New York, reprocessed spent fuel for six years before closing in 1972. Looking to expand the plant, the owners balked at the costs required for upgrades needed to meet new regulatory standards. Construction of a reprocessing plant in Barnwell, South Carolina, was halted in 1977 following the Carter administration's ban.

David Kramer PT

SANDRA HERRMANN/INTERNATIONAL OCEAN DISCOVERY PROGRAM/*JOIDES RESOLUTION* SCIENCE OPERATOR

Rebecca S. Robinson is a professor of oceanography at the University of Rhode Island in Narragansett and studies the links between ocean biology, chemistry, and climate in the geological past. **Sonia Tikoo** is an assistant professor of geophysics at Stanford University in California and uses paleomagnetism to study planetary magnetic histories, geodynamics, and impact cratering processes. **Patrick Fulton** is an assistant professor of Earth and atmospheric sciences at Cornell University in Ithaca, New York, and studies hydrologic and thermal processes in faults and fractures to better understand the physics of earthquakes.





Sea changes for scientific ocean drilling

Rebecca S. Robinson, Sonia Tikoo, and Patrick Fulton

An era of exploration and discovery beneath the seafloor is coming to an end. Yet there is much more to learn.

With acclaimed author John Steinbeck serving as historian, a group of US scientists and engineers set out in 1961 on a first-of-its-kind mission to drill through the oceanic crust and take the temperature deep beneath the seafloor.[1] Working in waters too deep to drop anchor, the team used a specially adapted barge equipped with a series of outboard motors that enabled them to hold position in the same location for weeks on end. The drilling vessel was topped with a specialized crane, known as a derrick, positioned over a hole in the center of the deck through which the drill string could be lowered. Steinbeck recognized the tremendous potential of the drilling mission, known as Project Mohole: exploring the vast, unexplored terrain beneath the oceans.

Rock samples collected in that first deep-ocean drilling project suggested that the oceanic crust was made of volcanic rocks—an important piece of information that supported the emerging theory of plate tectonics. The visionary project, although falling short of its stated mission of drilling into the mantle, advanced capabilities for both industry and science and inspired decades of scientific ocean drilling and international collaboration. Those efforts have produced a scientific infrastructure of technical, engineering, and managerial know-how, drillships, and a broad multidisciplinary science community of thousands of people that continues to produce groundbreaking discoveries and scientific advances. To read about the history of scientific ocean drilling, see the box on page 33.

Today scientific ocean drilling is positioned as a critical tool for addressing fundamental questions about Earth and its response to climate change, the origins and evolution of life, the hazards associated with earthquakes and tsunamis, and a host of other research areas. The future of scientific ocean drilling, however, remains uncertain as the US retires its drillship, the *JOIDES Resolution*; ends its current NSF-supported drilling program; and pauses to consider how to proceed.

A new international ocean drilling program will be launched on 1 January 2025 by the European Consortium for Ocean Research Drilling and Japan. It will operate expeditions using mission-specific platforms, with vessels and time frames selected to meet the science needs of each mission, rather than the routine two-month expeditions that have been a staple of *JOIDES Resolution* missions. The Japanese drilling vessel *Chikyu* and research vessel *Kaimei* will serve as two primary coring facilities for future scientific ocean discovery work. The stakes are high, and there is concern among the global Earth-sciences community, especially in the US, about losing the unique technical knowledge and collaborative framework honed over many generations. Data from the world's oceans hold the answers to many important outstanding science questions, but they may be harder to solve without a globally ranging drillship akin to the current *JOIDES Resolution*.

The ins and outs of scientific ocean drilling

The sampling of intact geological materials and acquisition of high-quality data from deep within Earth require a set of tools and techniques distinct from those used to drill for oil and natural gas or to construct underwater footings for turbines and bridges. Scientific drilling ships can maintain their position in a range of water depths and current, wind, and wave conditions; recover near-continuous rock and sediment cores in various geological materials; deploy logging instruments that characterize the geophysical properties of the subsurface; and install observatories for capturing dynamic *in situ* information deep underground. Such tools have transformed the ability to study Earth. The results have revolutionized human understanding of its history, geology, and ecology and revealed crucial information about processes that shape our planet.[2]

On the *JOIDES Resolution*, coring begins on the bridge, after the ship arrives at a destination and deploys thrusters that are part of the ship's dynamic positioning system. The thrusters, shown in figure 1, automatically maintain a position, which is critical for coring anywhere that anchoring is not feasible, such as in deep waters. A manual precursor of the technology debuted on the barge for Project Mohole in 1961. Dynamic positioning has since been widely adopted for research and industry purposes and has undergone numerous improvements.

Once in position, the ship prepares for coring by assembling 9.5 m pieces of pipe end over end beneath the derrick. The assembled pipe with a drill bit on the end, together known as the drill string, extends through a hole in the ship's hull, called the moon pool, to the seafloor. A plastic-lined core barrel is lowered through the interior of the pipe. A huge motor in the derrick provides torque for the pipe during drilling.

In soft sediment, a hydraulically actuated system plunges the inner core barrel and liner, with a cutting shoe at the tip, beyond the end of the outer pipe to recover a relatively pristine 9.5-m-long sediment core. The drillers then advance the pipe, replace the inner core liner, and prepare to shoot the next core. Typical depths of soft-sediment core recovery range from 300 m to 500 m below the seafloor but can reach as deep as 700 m (data from Shiny Laurel version 1.0.0, https://doi.org/10.5281/zenodo.10499014). A single hole can yield 30–70 individual cores.

In firmer sediments and basement rock, cores are collected by rotary drilling. The outer drilling pipe rotates through the rock or sediment while the nonrotating inner core barrel with lining advances and trims the core. The *JOIDES Resolution* has drilled down as far as 2100 m beneath the seafloor into the ocean crust. The record for the deepest ocean drilling hole was set by the *Chikyu* in 2019, when it drilled a hole 3250 m beneath the seafloor in the Nankai Trough off the coast of Japan.

The drill string, in its 9.5 m segments, is like a piece of limp spaghetti being lowered 3000–5000 m through the moving ocean. Despite the physical challenges of such a system, scientific ocean drilling has developed the capability not only to core in a specific location but also to thread the drill string back into previously occupied boreholes that have been equipped with a reentry cone and casing system, as shown in figures 1 and 2. The funnel-like

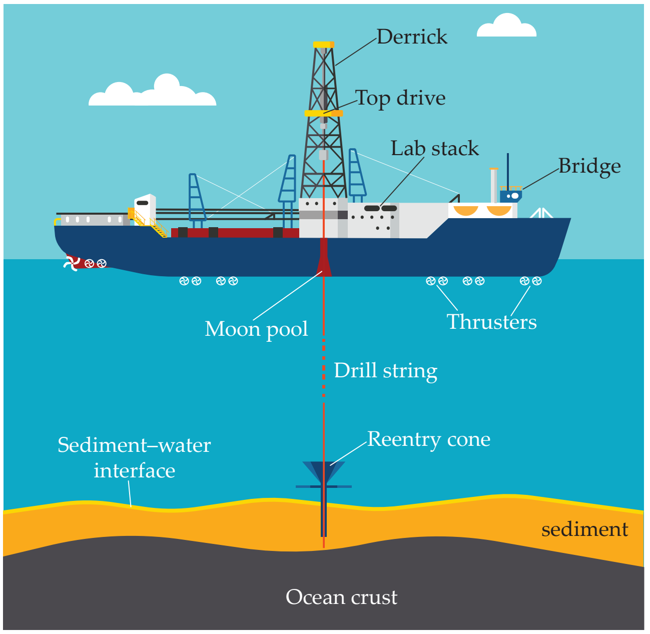


FIGURE 1. *JOIDES RESOLUTION* SCHEMATIC. The US scientific ocean drilling vessel will be retired at the end of 2024, with no replacement in line. (Adapted from International Ocean Discovery Program/*JOIDES Resolution* Science Operator.)

cone allows for reentry and deepening of a hole or for the installation of a borehole observatory—essentially a string of sensors in the seafloor—that can collect data *in situ* over time.

International multidisciplinary science

Joining a drilling expedition, either as science or technical staff, means becoming part of an international team that will typically spend two months together, working 12-hour shifts 7 days a week, to process, measure, and analyze geological materials and data acquired during the expedition (see figure 3). On the *JOIDES Resolution*, much of that work happens at sea; on the mission-specific platform expeditions, only time-sensitive work occurs at sea. Additional processing is done by expedition scientists in a shore-based laboratory. The goals of each expedition are carefully laid out years in advance, along with the technical needs, requirements for safe operating conditions, and essential staff needed to accomplish them.

A typical drilling day on the *JOIDES Resolution*, for example, involves the efforts of more than 100 personnel, including the captain, engineers, drilling team, catering staff, technical staff, and scientists. Drilling crews recover cores or place instruments in the borehole. Once a core is on deck, it is transferred to the technical staff for curation and logging of metadata and then to the scientific team for the collection of a comprehensive series of standard shipboard data and of expedition-specific data. The standard data collected shipboard—such as the core's age, chemical composition, and magnetic polarity and the presence of fossils—have been particularly important hallmarks of scientific ocean drilling. The reliable generation of simple yet diagnostic data provides reconnaissance information for evaluating the success of the current drilling, planning future sampling, and generating hypotheses.

Postcruise work follows up on those preliminary results, through additional sample collection, lab work, data processing, and modeling. Over time, the growing data sets facilitate the discovery of large-scale global patterns of change on Earth's surface through time and space—for example, a 15-million-year global history of organic carbon deposition in the ocean to study biological productivity[3] and a global survey of subseafloor biological respiration from pore-fluid data.[4] Work on the samples and data collected can continue for decades after their initial recovery and is integral to research, education, and training all over the world.

Unveiling geophysical processes

One of the founding motivations for scientific ocean drilling was to collect samples of rock from Earth's mantle. In May 2023, during expedition 399 of the International Ocean Discovery Program (IODP), the *JOIDES Resolution* attempted that goal again by drilling deep into the Atlantis Massif and collecting the longest continuous sequence of rocks with compositions similar to those found in the mantle.[5] Extensional faulting perpendicular to the Mid-Atlantic Ridge formed the Atlantis Massif and introduced lower crustal rocks to the seafloor. Data from that expedition will provide insight into the composition and structure of oceanic lithosphere.

Furthermore, interaction between water and rocks from the lower crust and mantle leads to a form of metamorphism known as serpentinization. Such reactions are hydrothermal alterations of the rocks that produce methane and hydrogen, which are used as energy sources by seafloor microbial communities. Serpentinization and other similar rock–fluid interactions may be occurring at the seafloors of icy ocean worlds in the outer solar system, such as Europa and Enceladus, and thus may create environments conducive to the origin and maintenance of microbial life.[6] As such, scientific ocean drilling plays a critical role as a proxy for understanding astrobiology.

The 2011 magnitude 9.0 Tōhoku-oki earthquake off the coast of Japan exhibited more than 50 m of slip on the fault all the way to the seafloor in the trench. Before that event, researchers had generally thought that such large amounts of earthquake slip were confined to much deeper sections of the fault where an earthquake rupture initiates. The shallow slip in the 2011 event led to an earthquake and a tsunami that was larger in magnitude than expected. Analyses of fault-zone core samples from the Nankai Trough and Japan Trench subduction zones, collected during IODP expeditions 316 and 343, respectively, have subsequently revealed evidence of previous large earthquake ruptures with shallow slip.[7,8] Understanding which faults have experienced large, shallow earthquake slip in the past has huge implications for constraining the conditions that produce tsunami hazards.

The IODP rapid-response drilling expedition 343/343T set out soon after the 2011 earthquake. It collected samples from the fault zone and installed a subseafloor borehole observatory that measured the heat generated along the fault by frictional resistance during the earthquake. The results reveal that the fault zone was incredibly weak—with little resistance to stop the rupture and dissipate energy.[9]

The ability to install observatories deep beneath the seafloor to acquire data and monitor subseafloor systems *in situ* is one of the most exciting and unique aspects of modern scientific ocean drilling (see figure 2). Within the past two decades, some sections of subduction-zone faults have experienced centimeters of slip over the course of hours to months without producing destructive earthquakes. Monitoring those slow-slip events

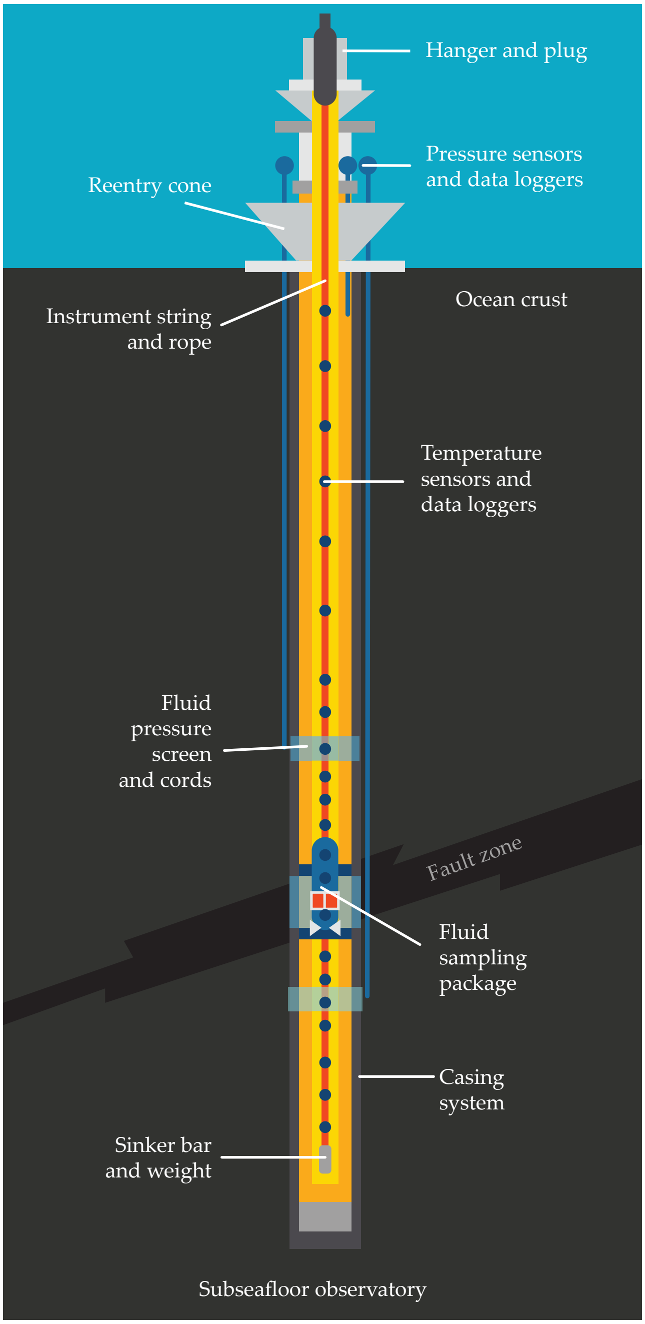


FIGURE 2. SUBSEAFLOOR OBSERVATORIES measure temperature and pressure changes that are used to identify subsurface fluctuations such as slow-slip events on megathrust faults.

is of particular interest for researchers because they affect the stress conditions on faults and can potentially trigger the fast earthquakes that produce damaging shaking.

Those fault systems are mostly far from shore, under the ocean, and difficult to monitor with land-based instruments. Subseafloor borehole observatories installed through scientific ocean drilling, however, have proven remarkably powerful in identifying and characterizing that slip behavior.[10] When even a tiny (roughly 1 cm) amount of slip occurs along a fault, it either squishes or dilates the surrounding rocks, causing the pore-fluid pressure in the rocks to increase or decrease. Those transient subseafloor pressure changes in the rocks are recorded and easily discerned from oceanographic and tidal fluctuations at the seafloor. Borehole observatories in the seafloor are thus more sensitive than approaches that use networks of seismometers and other seafloor georeferencing instruments.

In conjunction with the International Continental Scientific Drilling Program, IODP expedition 364 used a mission-specific platform in 2016 to collect approximately 800 m of drill core from the Chicxulub crater off the Yucatán Peninsula in Mexico. The 66-million-year-old, roughly 200-km-diameter impact crater is linked to the Cretaceous–Paleogene mass extinction that killed off 75% of the world's species, including all nonavian dinosaurs.

Geological materials recovered by the expedition have revealed how large impact events shock and deform the crustal rock and transport large blocks hundreds of meters in size from depths of 10 km to near planetary surfaces within a span of minutes.[11] Cooling of initially molten rocks in the center of the Chicxulub crater drove a vast hydrothermal system for potentially millions of years. Thermophilic bacteria still reside in the crater, which suggests that postimpact hydrothermal systems can spawn ecosystems supported by chemosynthesis.[12] Paleontological observations from sedimentary rocks overlying the crater indicate that life returned to the waters and sediments above ground zero within a span of years, highlighting the ability of life to rebound following a global catastrophe. (For more on research from the Chicxulub core samples, see Physics Today, April 2021, page 64.)

Illuminating future climate by studying the past

Scientific ocean drilling has provided many of the data that inform us about past climate change and the resulting effects on the biosphere over the past 200 million years. Because drill cores are collected around the world, ocean drilling enables acquisition of spatially comprehensive data sets that can shed light on regional and global changes in temperature, sea level, ocean circulation, monsoons, evolution of marine microorganisms, and more.[13,14]

Analyses of cores from the ocean floor have elucidated drivers of long-term global warming and cooling, the evolution of tropical monsoon systems, the expansion and contraction of large ice sheets, and the interactions between high-latitude ice growth and low-latitude climates. A series of expeditions encircling the Indian Ocean from 2013 to 2016 revealed the development and intensification of seasonal monsoons in Asia, Africa, and Australia that emerged at least in part as a consequence of tectonically driven Himalayan uplift and mountain building.[13] (For more on seasonal monsoons, see the article by Michela Biasutti, Mingfang Ting, and Spencer Hill, Physics Today, September 2023, page 32.)

Coring deep into sandy, submarine fans, built by large rivers draining sediments from Asia, provided data to reconstruct rates of tectonic uplift and landscape evolution and the impact of rising landmasses on ocean and atmospheric circulations. Penetration through the thick river-derived sediment packages proved difficult and limited the depth of drilling, so the history of monsoons before about 15 million years ago remains unsampled.

Earth's polar ice sheets serve as major drivers of global climate and ocean circulation. Decades of work in the deep ocean have documented through geochemical data the variation in the size of polar ice sheets. Yet records from closer to the largest ice sheets are required to truly understand controls on ice-sheet dynamics, the relationship between ice-sheet history and sea level, the temporal evolution of Southern Ocean circulation, and the interplay between ice, Southern Ocean circulation, and ocean ecosystems. The IODP's Southern Ocean expeditions, including four recent ones conducted in 2018–19, provide unprecedented details about past warm periods, such as evidence for the collapse of the West Antarctic Ice Sheet triggered by ice loss in the Amundsen Sea around 4 million years ago.[15] They also highlight the close coupling between carbon dioxide, ice-sheet dynamics, and ocean temperature.[16] (For a map of the sites drilled over a 54-year period, see figure 4.)

FIGURE 3. A DAY IN THE LIFE on the *JOIDES Resolution*. At any given moment, scientists, technicians, and crew members may be working, eating, sleeping, or relaxing on the ship, which operates 24/7. (Courtesy of the International Ocean Discovery Program and the *JOIDES Resolution* Science Operator. Photographers are Tim Fulton, top left, middle left, and second from bottom right; Rosie Sheward, bottom left; Takuya Sagawa, top right; Yiming Yu, second from top right; and Trevor Williams, bottom right.)

The future of scientific ocean drilling in the US

With the end of IODP2 scheduled for 2024, the international community began planning for the future in 2018. Efforts included developing a broad, forward-looking framework of science priorities[17] and discussing what a new drilling vessel needs to carry out US and global science priorities.[18]

Yet in March 2023, NSF announced that the future of US-supported scientific ocean drilling was uncertain because the cooperative agreement between NSF and Texas A&M University, the operator of the *JOIDES Resolution*, would cease in 2024, four years before the ship's environmental permit expires in 2028. At present, a pathway for US scientists to collect samples from deep beneath the seafloor from 2024 to 2028 remains unclear.

As of the end of 2023, no planning for a new ship has begun. (For more on the *JOIDES Resolution*'s retirement, see Physics Today, September 2023, page 21.)

The decision to retire the *JOIDES Resolution* has numerous impacts in the US. First and foremost, a tremendous amount of science will be put on hold. Most available drilling platforms do not operate in water deeper than 3000 m or have the capability to recover cores from deep within the sediment or crust. Delays in the decisions about a new drillship indicate that the interruption in accessing much of the subseafloor could extend out to 2030 or beyond. An extended period without new data, samples, or shipboard training means that the US is limiting the advancement of a generation of geoscience researchers and technicians.

With an uncertain future for new sampling, some of the community will continue to work with the legacy assets (samples and data) that have been carefully curated by the scientific ocean drilling communities. Yet there are limitations to what has been recovered and curated and to the volume and viability of the remaining materials. For example, geomicrobiology research requires freshly recovered materials to capture the biological signatures of life before the samples degrade in storage or even from the changing environmental conditions shipboard.

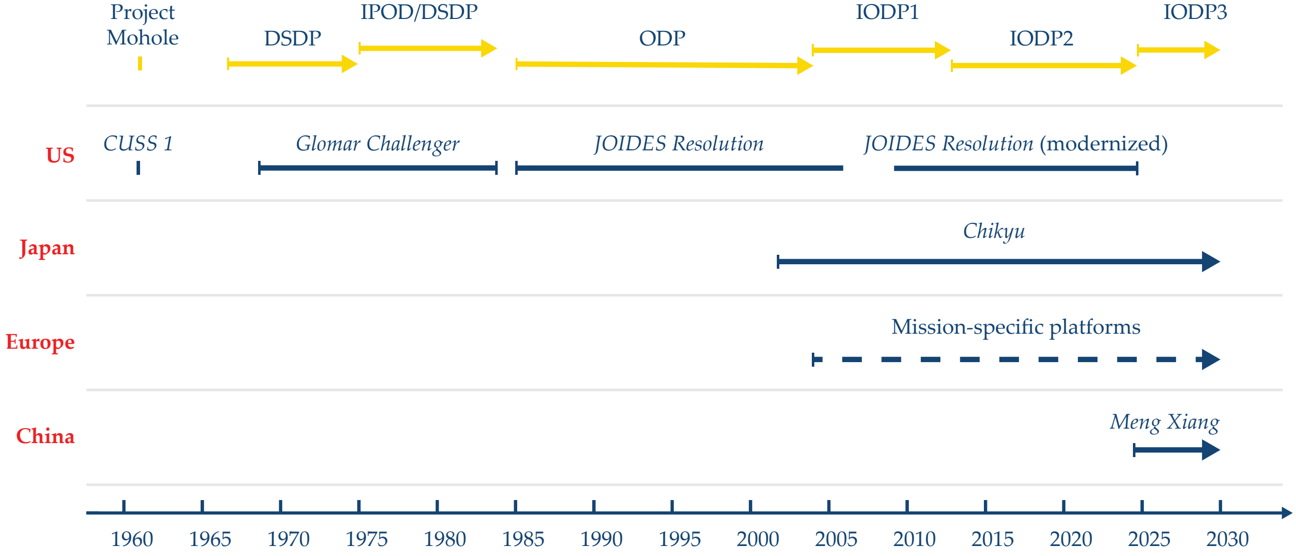
History of scientific ocean drilling

The first scientific ocean drilling expedition, Project Mohole, was conducted in 1961. Five years later, in 1966, NSF funded the establishment of the Deep Sea Drilling Project (DSDP). Starting in 1975, the US was joined by several partners, including France, Japan, the UK, the USSR, and West Germany, to create an international collaboration under the acronym IPOD, for International Phase of Ocean Drilling. That stage established the science-enabling infrastructure to provide technical and logistical staff, a publications office, and funding mechanisms. The infrastructure has evolved over time. With the advent of personal computing and advances in global communications, for example, scientific ocean drilling incorporated information technology and database development.

From 1968 to 1983, the DSDP conducted a series of scientific expeditions with the drilling vessel *Glomar Challenger* and recovered sediment and rock cores from around the world's oceans that provided evidence for plate tectonics, geological-scale climate change, and the evolution of life. The success of the DSDP led to the establishment of its successor, the Ocean Drilling Program (ODP), in 1983 and the acquisition and adaptation of a successor drilling vessel, the *JOIDES Resolution*, which still operates today.

The next phase was conducted in two parts, the Integrated Ocean Drilling Program (IODP1), established in 2003, and the International Ocean Discovery Program (IODP2) which began in 2013. The IODP1 expanded the scope of drilling to include not only the US-run *JOIDES Resolution* but also the *Chikyu* science vessel, designed to drill down to 7000 m below the seafloor and operated by the Japan Agency for Marine-Earth Science and Technology. The IODP1 also included a flexible mission-specific platform program run by the European Consortium for Ocean Research Drilling (ECORD), which currently leases alternative commercially available drilling platforms needed for environments that cannot be drilled with the *JOIDES Resolution* or *Chikyu*. The next international ocean drilling program, IODP3, will be launched on 1 January 2025 by ECORD and Japan, centered around the use of mission-specific platforms.

The *JOIDES Resolution* has been the primary workhorse for scientific ocean drilling; it has hosted about 80% of the expeditions conducted since 2013 because of its flexibility to work in a range of environments and its evolving capabilities. With the scheduled end of its long-term lease in 2024, the potential for scientific progress over the next decade or more is limited by where and how deep the *Chikyu*, mission-specific platform vessels, and the new Chinese vessel *Meng Xiang* can drill.



TIMELINE OF SPECIALIZED SCIENTIFIC OCEAN DRILLING VESSELS

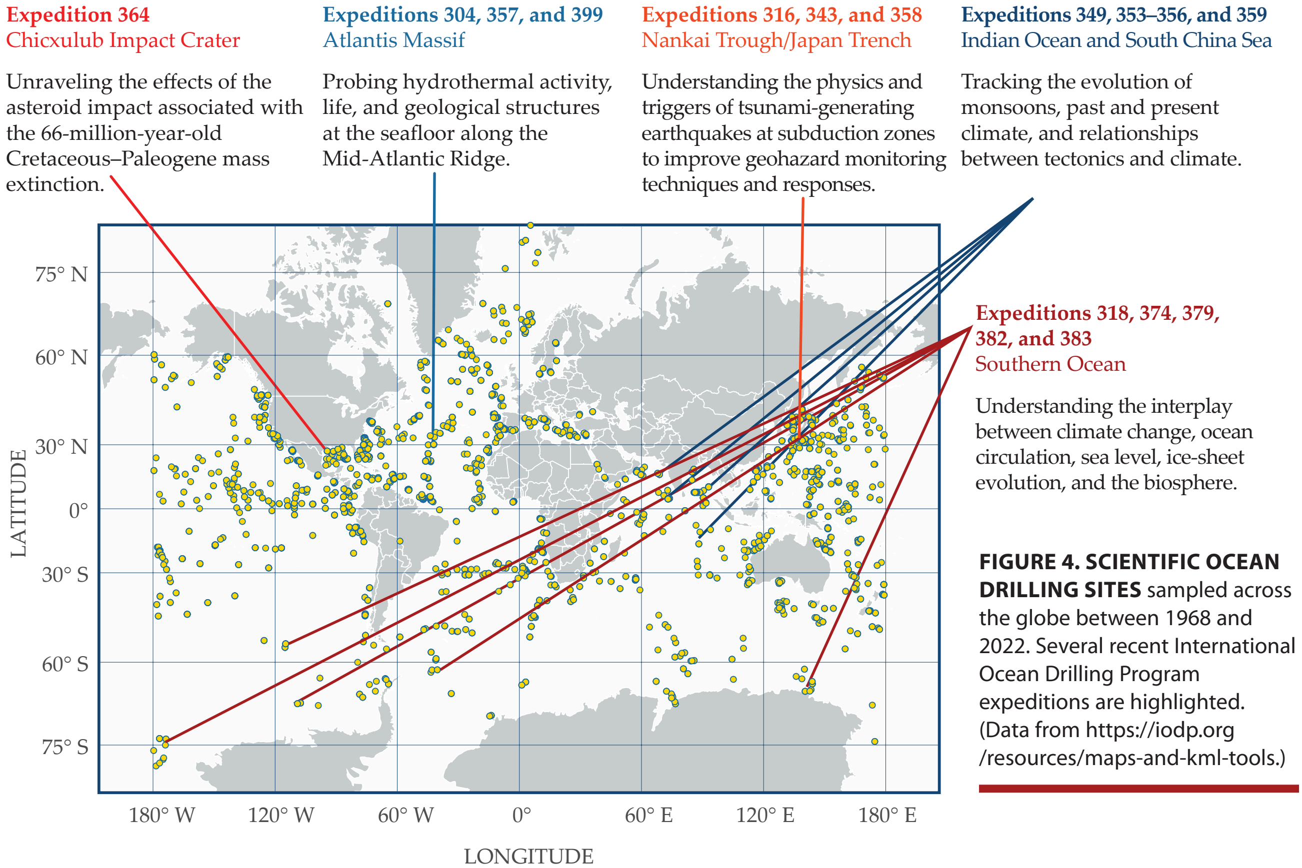


FIGURE 4. SCIENTIFIC OCEAN DRILLING SITES sampled across the globe between 1968 and 2022. Several recent International Ocean Drilling Program expeditions are highlighted. (Data from https://iodp.org/resources/maps-and-kml-tools.)

Observatory-related science that requires new *in situ* measurements cannot be conducted without an appropriate ship for drilling a borehole and installing and recovering the instrumentation and data. Although curated cores may be useful to future climate-oriented work, the coverage of the collections is by no means global in time or space, and some key intervals that were sampled are now depleted.

Scientific ocean drilling has proved incredibly powerful as a means to train students from universities across the US and the world in drilling, collaborating across various science and engineering disciplines, and understanding and interpreting what lies deep underground. The special skills and expertise developed from that work extend beyond the academic realm and are critical for a workforce that will help the US transition to a low-carbon future, especially in the fields of geothermal development, groundwater and environmental management, and carbon dioxide sequestration. Because drilling and geotechnical training opportunities will be sharply limited, losing that science engine will have far-reaching implications. A hiatus in drilling also means a cessation in the development of new technologies that come from the immediacy of needing a problem solved to achieve a specific goal. Because the US has been the global leader in scientific ocean drilling since the field's inception, the current uncertainty is rippling out into the international Earth-sciences community.

After sailing on the first deep-ocean drilling project back in 1961, John Steinbeck wrote that "on this first touching of a new world the way to discovery lies open" (reference 1, page 122). While we celebrate the remarkable accomplishments that scientific ocean drilling has produced since then, we hope that the world of science discovery beneath the oceans will remain accessible for the next generation of US scientists and engineers seeking to tackle Earth's biggest mysteries and uncertainties.

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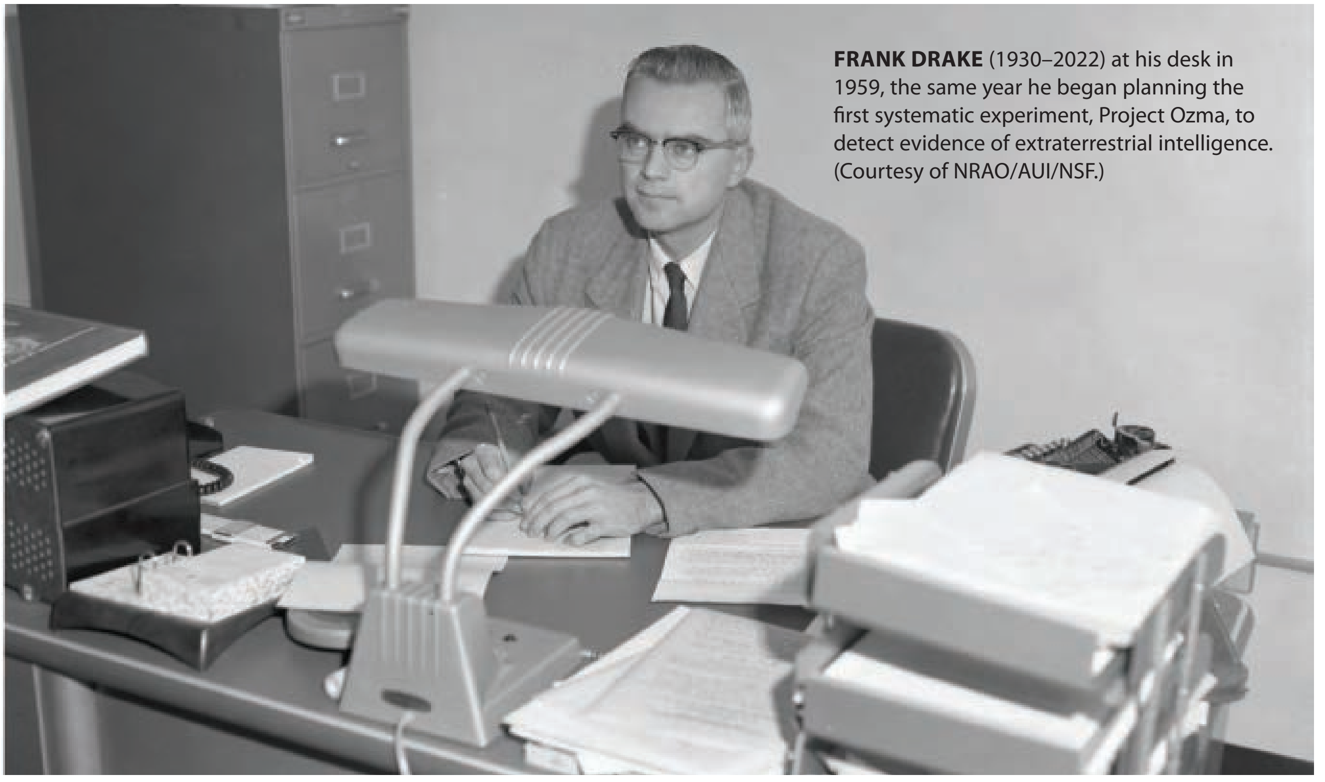
SETI, artificial intelligence, and existential projection

Rebecca Charbonneau

SETI's birth during the Cold War may have prompted consideration of existential threats to humanity and proposals for using nuclear bombs to communicate with extraterrestrials.

On an autumn afternoon in 1971, a group of scientists—mostly astronomers—sat in an auditorium in the Soviet Union at the first US–Soviet conference on the search for extraterrestrial intelligence, or SETI. The topic of discussion that afternoon was artificial intelligence (AI) and how it might revolutionize or destroy our world.

Some things never change. Today AI has a strong connection to SETI and to astronomy more broadly. AI is used to analyze vast amounts of astronomical data generated by powerful computer simulations and detailed sky surveys. Initiatives such as Breakthrough Listen use AI to analyze hundreds of hours of data from such telescopes as the Green Bank Telescope in West Virginia, with astronomers hoping to find signals that exhibit expected attributes of alien technosignatures. In sum, AI helps astronomers become better at identifying, predicting, and understand-



FRANK DRAKE (1930–2022) at his desk in 1959, the same year he began planning the first systematic experiment, Project Ozma, to detect evidence of extraterrestrial intelligence. (Courtesy of NRAO/AUI/NSF.)

ing features of our universe—and does it all much faster than humans alone can.[1]

But the great strides have also brought about great panic. In the past couple of years, we have seen the development and mass deployment of next-generation AI tools, such as ChatGPT. That development has spurred both excitement and concern over AI's impact on our world. Citing "profound risks to society and humanity," a group of scientists, policy analysts, and businesspeople authored an open letter proposing a pause on giant AI experiments.[2] Six days later *Time* published an article by AI theorist Eliezer Yudkowsky titled "Pausing AI developments isn't enough. We need to shut it all down," which made the bold assertion: "If we go ahead on this everyone will die, including children."[3]

In that article Yudkowsky likened developing "superhuman AI" to encountering an advanced alien civilization. Technologists warn about the singularity—a term coined by mathematician and computer scientist Vernor Vinge and popularized by futurist Ray Kurzweil—which denotes a hypothetical future moment when AI will surpass human intelligence. In 2018 Elon Musk warned that AI might become an "immortal dictator from which we can never escape."[4] In other words, AI has prompted a full-blown existential panic.

AI anxiety

Some might be inclined to dismiss that hand-wringing as a form of neo-Luddism. The word "Luddite" refers to a group of 19th-century British textile artisans who were concerned that unskilled mechanized operators were depriving them of their means of livelihood and launched a violent movement in which they attacked and destroyed factories and machinery.

Today the term Luddite is often used to dismiss those with concerns about new technologies as being technophobic and resistant to progress. But the 19th-century Luddites were not mere technophobes. Social historians have shown that rather than simply destroying machines, they also lobbied various local and national authorities for new regulations and labor laws.[5] In other words, it was not the technology that they feared but the unfair labor practices that took advantage of technology to disenfranchise laborers.

New technologies frequently spark anxieties, but often not without good reason. Social scientists and policymakers know AI has myriad problems, which are not necessarily a result of the technology itself but, rather, how it is used. The American Civil Liberties Union has tracked the ways in which AI can have harmful social impacts. For instance, AI can perpetuate housing and hiring discrimination through biased algorithms and flawed data sets, leading to unjust denials of housing and job opportunities.

Indeed, AI worried SETI scientists long before the development of ChatGPT. In 1965 Soviet SETI scientist Iosif Shklovsky wrote about possible existential threats facing humanity and cautioned that "profound crises lie in wait for a developing civilization and one of them may well prove fatal," giving the example of "a crisis precipitated by the creation of artificial intelligent beings."[6]

Shklovsky's concerns about AI were just a drop in the bucket. Tasked with the mission of seeking out and possibly communicating with extraterrestrial civilizations, should they exist, SETI scientists had to think about the big picture: the nature of life, civilization, intelligence, and, critically, what can bring those things to an end.

After all, if there were a cosmic silence—if astronomers never detect signs of extraterrestrial life—it might reveal a universal truth on the nature of intelligent life. Perhaps, as Shklovsky warned, extraterrestrial civilizations had too many crises to

PROJECT OZMA. At the National Radio Astronomy Observatory in Green Bank, West Virginia, Frank Drake and his colleagues used the 85-foot dish antenna **(right)** to examine the region of space around two nearby Sun-like stars, Tau Ceti and Epsilon Eridani, in a search for artificial radio signals. **(Left)** The telescope's control room is shown in 1961. Although the search to find evidence of extraterrestrial intelligence, known as Project Ozma, didn't yield definitive results, it ignited a global scientific conversation. (Courtesy of NRAO/AUI/NSF.)

overcome for them to survive long enough to communicate with others. SETI necessitates the pondering of such possibilities.

Astronomy more broadly, even outside of SETI, carries similar existentialist considerations. Many of the celestial phenomena that astronomers study—black holes, supernovae, and stellar flares, to list just three—can be planet killers. They have roughly determined the expiration date of our own planet, when our sun will expand enough to swallow Earth or at least get close enough to scorch it into a searing hot rock. Cosmologist Katie Mack famously wrote about what she calls "the end of everything."[7] Physicists and astronomers can make projections not only for the end of us but for the end of the entire universe. It seems natural, then, that astronomers who worked in SETI might be inclined to speculate on how civilizations end.

In doing so, SETI scientists imagined not only dozens of ways in which life might exist in the universe but also dozens of ways it might die. SETI had its finger on the pulse of earthly anxieties, and its preoccupation with Earth's technologies—especially the harmful ones—ultimately shaped the character of its search.

The Cold War

Given SETI's existentialist vein, it should come as no surprise that the field was founded during the Cold War. More specifically, it grew out of the field of radio astronomy, which rapidly expanded at the end of World War II, partly as a result of new technologies such as radar. After the war, some radar technicians and operators began careers in astronomy.

But although radio astronomy developed in dozens of countries after the war, SETI was nearly exclusively conducted in the US and the Soviet Union, perhaps because of the influence of the space race prompting consideration on what we might find "out there."

The SETI community generally considers the first search for extraterrestrial civilizations to have been conducted in 1960 by the US astronomer Frank Drake. His search, named Project Ozma, took place at the National Radio Astronomy Observatory in Green Bank, West Virginia, using its new 85-foot telescope. The project got its name from Princess Ozma, a character in L. Frank Baum's Oz novels (on which the popular film *The Wizard of Oz* was based).

Drake explained that Oz was "a land far away, difficult to reach, and populated by strange and exotic beings" (reference 8, page xi), perhaps not unlike the lands and creatures he wished to communicate with. In the novels, the fictitious narrator employs wireless radio technology to establish communications with the faraway realm of Oz. Like the books' narrator, Drake wanted to use radio to speak with exotic worlds "somewhere over the rainbow."

Project Ozma observed two Sunlike star systems, Tau Ceti and Epsilon Eridani, at a wavelength close to the 21 cm hydrogen line. Drake's idea was inspired but simple: If there are intelligent extraterrestrials who have developed radio technology just as we have, then we might be able to detect them using radio telescopes on Earth. The results of the project were null, but they led to many subsequent searches by others. A new subfield of astronomy was born.

SETI astronomers held a cosmopolitan perspective, with Drake and others like him predicting that the detection of extraterrestrial intelligence might result in a wave of peace and unity on our own planet. In 1992 he wrote,

> I fully expect an alien civilization to bequeath us vast libraries of useful information, to do with as we wish. This "Encyclopedia Galactica" will create the potential for improvements in our lives that we cannot predict. During the Renaissance, rediscovered ancient texts and new knowledge flooded medieval Europe with the light of thought, wonder, creativity, experimentation, and exploration of the natural world. Another, even more stirring Renaissance will be fueled by the wealth of alien scientific, technical, and sociological information that awaits us. (reference 8, page 160)

Other SETI scientists shared that perspective, and they facilitated collaboration between Soviet and American astrophysicists. Even so, the Cold War backdrop presented challenges to the new, optimistic science. In trying to cooperate in

PRISCILLA LIGHTS UP THE SKY. Conducted on 24 June 1957 as a part of Operation Plumbbob at the Nevada Test Site, the "Priscilla" nuclear detonation was meant to showcase advancements in nuclear testing technology. The explosion provided data for Cold War–era nuclear weapons development but also raised concerns about environmental and health effects. (Courtesy of the US Department of Energy.)

their searches, Soviet and American SETI scientists discovered that it was difficult to communicate with each other, let alone extraterrestrials, because of political barriers like travel bans, mail interference, and, perhaps especially, interference from the intelligence community.

Alien intelligence

Drake first developed the idea to search for artificial radio signals during a period when, for the first time in our known history, artificial radio signals pervaded outer space. Spy satellites and spacecraft were growing in number, and radio-astronomy infrastructure was being used for both science and military applications. The same telescope that could detect evidence of extraterrestrial intelligence could also track an intercontinental ballistic missile.[9]

The tension between those applications created a challenge for SETI. While it promoted international collaboration across the Iron Curtain, it was also entangled with military and governmental interests. Because their goals were often the same—detecting narrowband, artificial signals in space—SETI scientists became adept at developing techniques that were exploited by the intelligence community for deep-space listening.[10] Thus, in many ways, SETI embodied the tensions of the 1960s: It imagined a hopeful future in space during a present marked by military conflict and nuclear threats.

That duality—a science rooted in both internationalism and warfare—may be what prompted SETI's consideration of existential threats. Carl Sagan raised the concern in the book *Intelligent Life in the Universe*, which he coauthored in 1966 with Shklovsky. They wrote, "Another question of some relevance to our own time, and one whose interest is not restricted to the scientist alone, is this: Do technical civilizations tend to destroy themselves shortly after they become capable of interstellar radio communication?" (reference 11, page 358).

Drake had similar concerns. At a conference in Green Bank in 1961, he revealed the now-famous Drake equation, which was designed to help SETI scientists organize discussions on the number of extant extraterrestrial civilizations in our galaxy. His equation's final variable L stands for a civilization's longevity. Drake understood that it was important to calculate not only how many intelligent civilizations might arise in our galaxy but also how long they would survive.

When Drake presented his equation, the nuclear arms race was reaching a head; less than one year later, the Cuban Missile Crisis would bring the world to the brink of disaster. The longevity of intelligent technological civilizations was a pressing question.

The great filter

Despite the assumption that intelligent life could be abundant in the universe, SETI scientists have long lacked any conclusive evidence of a message from an extraterrestrial intelligence. In response to the apparent cosmic silence, in 1950 physicist Enrico Fermi famously asked, "Where are they?" Indeed, the Fermi paradox, as it is now known, refers to the seeming contradiction between the high probability of extraterrestrial life existing in the universe and the lack of evidence for alien civilizations.

Although many SETI scientists attribute that absence to the dearth of comprehensive searches, some theorists began to propose the existence of what they call a "great filter," which acts as an obstacle preventing intelligent civilizations from establishing contact with one another. Think of the filter as a probability barrier—hurdles that life forms have to face at various points in their development.

The great-filter theory posits that highly unlikely evolutionary transitions must occur for an Earthlike planet to generate an intelligent civilization capable of being detected by our current technology. The great filter can either be behind us—implying that we have already surmounted a highly improbable event that enables our civilization's development—or ahead of us. In the latter case, it might come in the form of potential disaster, such as self-destruction by our own technology.

Consideration of death by atomic bomb colored many aspects of SETI's early thinking. At that first US–Soviet conference in 1971, ideas for contacting extraterrestrials were mixed with solutions for the nuclear arms race. James Elliot, an astronomer at Cornell University's Laboratory for Planetary Studies, presented a paper called "X-Ray pulses for interstellar communication," a benign title for a radical idea. Elliot proposed that nuclear weapons could serve as an announcement message from Earth when attempting to contact extraterrestrial beings.

If the US and the Soviet Union combined their nuclear arsenals to create a single large explosion far from Earth, he suggested, the emitted x rays could potentially be detected at a significant distance by intelligences on other worlds. In short, nuclear disarmament and extraterrestrial contact could be handled at the same time.

Andrei Sakharov, a prominent physicist, disarmament ac-

PREPARING A TIME CAPSULE. On 4 August 1977 at Cape Canaveral, Florida, Voyager project manager John Casani holds a small US flag that was later sewn into the thermal blankets of the Voyager spacecraft. The Golden Record, full of pictures and sounds, and its cover are laid out below Casani, while *Voyager 2* is in the background. The snapshot encapsulates the tensions between nationalism, signified by the US flag, and the universalism of the Voyager mission: The record carries a message from Earth to extraterrestrial beings. (Courtesy of NASA/JPL-Caltech.)

tivist, and key figure in the Soviet thermonuclear project, proposed a different communication system that also leveraged thermonuclear explosions. He suggested placing a series of explosions at various locations in our solar system to make flash lamps that could be used to communicate simple messages, such as primary number sequences.[12]

It is not a coincidence, of course, that the two scientists proposed nuclear solutions for such communications. The nuclear arms race defined much of the Cold War period and fear of the bomb loomed in the minds of civilians and scientists alike. During the 1960s and 1970s, the Soviet Union and the US each accumulated alarming arsenals of thousands of nuclear warheads—more than 10 times the amount required to render Earth uninhabitable to humans.

Many SETI scientists became avid antinuclear activists. In 1983 Sagan authored an essay titled "Nuclear war and climatic catastrophe: Some policy implications," published in *Foreign Affairs*. He argued that unless the US and the Soviet Union halted their arms race, humanity faced a high risk of extinction. The following year, he coauthored a book titled *The Cold and the Dark: The World After Nuclear War*, in which he popularized the concept of nuclear winter, a dire climate catastrophe that might be caused by nuclear war.

Philip Morrison, one of the participants in the 1971 US–Soviet Union SETI conference, had held a prominent role in the Manhattan Project and supervised the construction of the atomic bomb that detonated over Nagasaki, Japan. Following his firsthand observation of the catastrophic aftermath as a member of the Manhattan Project's survey team, Morrison transformed into a staunch advocate against nuclear weapons and established the Federation of American Scientists and the Institute for Defense and Disarmament Studies. He was perhaps more acutely aware of the devastating effects of nuclear technology than most other scientists and argued that one of the main benefits of SETI is that it is a tool that reveals our own future.

Morrison proposed calling SETI the "archaeology of the future." As he explained it, although studying the past through archaeology is fascinating because it informs us about our own history, SETI grants us the opportunity to explore our future because it shows what we have the potential to become. He claimed that SETI was "a missing element in our understanding of the universe which tells us what our future is like, and what our place in the universe is. If there's nobody else out there, that's also quite important to know."[13] Such thinking was, of course, highly deterministic. Over time, SETI scientists' existential fear had turned into existential forecast. They began to project their concerns about Earth and our civilization onto their expectations of what they might find in the universe.

The cosmic mirror

We might call this projection the cosmic mirror, a popular concept that suggests SETI might unify the world because it helps human beings to see themselves in a cosmic context. SETI scientist Jill Tarter once defined the cosmic mirror in an article for CNN, describing it as "the mirror in which all humans can see themselves as the same, when compared to the extraterrestrial other. . . . It is the mirror that reminds us of our common origins in stardust."[14]

But there's another side to the cosmic mirror. Although it can remind us of our common origins, it can also highlight our problems and conflict. Take, for example, the creation of the Voyager program's Golden Record. Designed in part by SETI scientists, including Sagan and Drake, the phonograph record was a message launched aboard the *Voyager 1* and *Voyager 2* spacecraft. Sagan and his team wanted to include on the record a diverse selection of sounds, images, and greetings that were intended to convey to potential extraterrestrial civilizations a snapshot of humanity's cultural and scientific achievements.

Despite the intended extraterrestrial focus, however, the team encountered unexpected terrestrial challenges. Recognizing the need to eschew an American bias, Sagan sought to include greetings in various languages. Limited on time, he visited the UN headquarters and asked all of the delegates to record a greeting in their native language, ensuring a diverse representation of humanity. While moving forward with the recordings, however, he quickly realized that all the chiefs of delegations were male—there would be no representation of a woman's voice.[15]

That realization sparked a crucial question about the record's design. Should it accurately depict the world and acknowledge world leadership's gender imbalance, which stems from a history of patriarchy? Should it show Earth as it truly is, including its horrors and injustices? Ultimately, the team chose a more positive portrayal and avoided depictions of violence and negativity.

The cosmic mirror can also be used to show how our anxieties about technology are manifested in our ideas about the universe. SETI scientists anxious about the rise of AI predict that we will find AI in outer space—in fact, it might be all we find. Shklovsky and Sagan once wrote that we "will some day very likely be able to create artificial intelligent beings which hardly differ from men, except for being significantly more advanced. Such beings would be capable of self-improvement, and probably would be much longer-lived than conventional human beings" (reference 11, page 486).

A cosmos populated mostly by technological beings is sometimes referred to as the "postbiological universe." Former NASA chief historian Steven Dick coined the phrase and argued that "cultural evolution over the long time scales of the universe has resulted in something beyond biology, namely, artificial intelligence." He defined the postbiological universe as "one in which the majority of intelligent life has evolved beyond flesh and blood intelligence, in proportion to its longevity."[16] Scientists who prescribe to the postbiological-universe theory believe that we are far more likely to encounter technology than biological life as we explore the universe.

With the rise of new AI technologies, a renewed interest has emerged in the postbiological universe and the potential proliferation of AI in it. Harvard University astronomer Avi Loeb, for example, recently made headlines for saying that small metal spheres found in meteor fragments on the seafloor were potentially from "a spacecraft from another civilization" and for telling the *New York Times* that it was "most likely a technological gadget with artificial intelligence."[17]

Although those claims have come under scrutiny, many SETI scientists agree that AI is what they are most likely to find in their search for extraterrestrials. SETI Institute scientist Seth Shostak has made the point that any aliens humanity should expect to encounter are likely past the point of AI development, considering that humans were able to accomplish the feat so quickly after inventing radio technologies.[18] Clearly, the anxieties and hopes we hold about our own technological civilization shape the way we imagine other worlds.

What to make of all this? It would be wrong to dismiss SETI's value because of these earthly trappings. In some sense, its ability to keep its fingers on the cultural pulse is what helps SETI transform and develop creative new strategies.

For example, the First Penn State SETI Symposium, held in 2022, had talks focused on "pollution SETI," which purports to identify evidence of industrial activity in exoplanetary atmospheres. One new NASA-funded initiative, Categorizing Atmospheric Technosignatures, aims to study exoplanetary atmospheres to create a catalog of potential atmospheric technosignatures, which might include known pollutants like chlorofluorocarbons.

During a period in Earth history when we are extraordinarily concerned with our planet's health, it occurs to us that perhaps we are not the only civilization to mistreat our home world. In the post-Cold War period, perhaps we have not forgotten the existential threat of the nuclear bomb, but our focus has shifted as we face other technologically rooted threats, such as climate change.

Throughout its history, SETI has considered the threats our world faces and developed optimism that humanity might overcome them. Although it is sometimes marked by a troubling determinism, which might hinder clearer thinking about the possibility of life elsewhere in the universe, SETI has led its practitioners to fight for scientific internationalism and activism against technological tyranny.

As seen in the idea of using nuclear arms as messages, SETI shows how the technological threat is not truly technical, but societal. Many of our existential threats, be they pandemics, natural disasters, or AI, are rooted in how our society chooses to use technology. Behind the word "intelligence" in SETI is a small but persistent worry that perhaps intelligent civilizations are not intelligent enough—that is, not intelligent enough to avoid destroying themselves.

The fact is that we know nothing about alien intelligence or the way technological societies—other than our own—progress. Instead, we project our anxieties about our own civilization onto extraterrestrials.

We are unlikely to learn much about the true nature of extraterrestrial civilizations from such speculative research, but in observing those patterns of deterministic forecasting, we may see how our predictions for extraterrestrials are tied up in our projections for our own civilization's future. Just as Cold War–era SETI motivated scientists to cooperate, the introspection that the field fosters might prove more successful at prompting global peacemaking than the actual discovery of an alien civilization.

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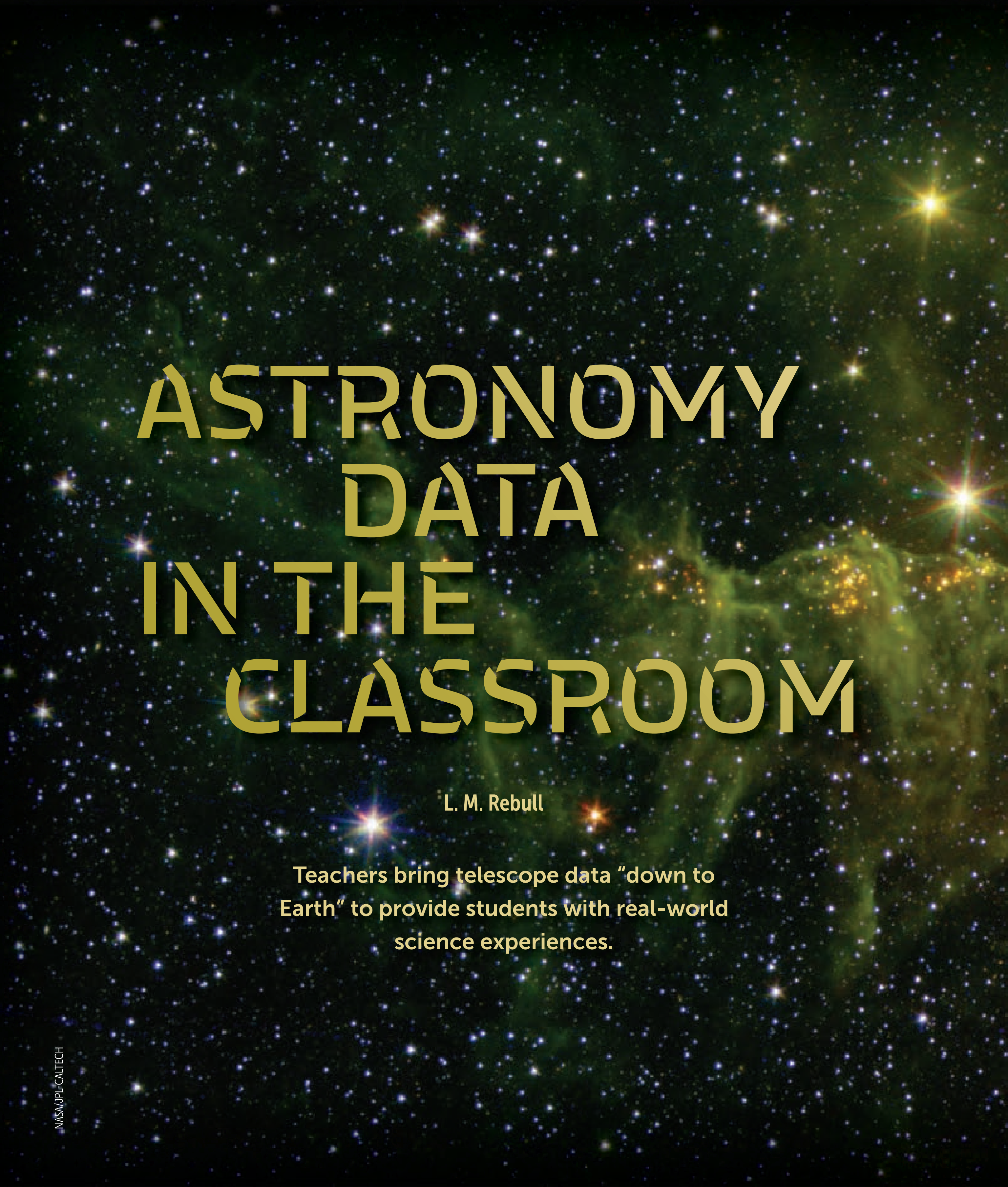

ASTRONOMY DATA IN THE CLASSROOM

L. M. Rebull

Teachers bring telescope data “down to Earth” to provide students with real-world science experiences.

NASA/JPL-CALTECH

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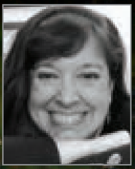


I will never forget the first science teacher training workshop I attended. I was in graduate school in astrophysics at the University of Chicago, and the Adler Planetarium hosted the workshop. We were given an image of the Sun with a large prominence at the lower right. After a brief introduction to the software, we were asked how many Earths fit underneath the prominence, given the image's pixel scale. I measured the prominence's height radially, calculated the ratios, and figured that it was about three Earths high. Simple enough, I thought, and I started to look around me. The gentleman to my right was completely overwhelmed. He had no idea how to approach the problem and resorted to telling me about all the teaching awards he had won.

THE 2022 NITARP TEAMS during their summer visit to Caltech. NITARP is a program that partners small groups of educators and students with a research astronomer for a 13-month-long authentic astronomy research project. It also includes a summer research trip. Here, one educator is experiencing an "aha" moment when something finally "clicked." (Courtesy of David Friedlander-Holm/Luisa M. Rebull.)

When we reconvened and shared our measurements, I discovered that many of the participants had interpreted "underneath" in strictly Earth-based terms—that is, up and down on the screen. Even those of us who determined "height" in the same way arrived at slightly different numbers, and we launched into a fascinating discussion of measurement error. Many participants were uncomfortable with there being so many correct answers.

All of those things—working with real data, angular measurements on the sky, ratios, significant figures, measurement error, and even determining which direction is "up"—are second nature to professional astronomers, but maybe not for many or even most middle and high school teachers.

Science teachers in the US, thanks to the Next Generation Science Standards, are now being asked to teach science in ways that they themselves were not taught—using real data and approaches that more closely mimic those of scientists.[1] There is a demonstrable need for teachers—and, therefore, students—to have an opportunity to do stuff that we, as trained scientists, take for granted. Astronomy is special among the sciences in that the public is already considerably interested in it, and multiple petabytes of multiwavelength research-grade data are available online for free to anyone. There are many ways to access those data, at many different levels, suitable for elementary through college students, educators at all levels, and the general public. Let's dive in!

Citizen science on the Web

The easiest way to start working with real astronomy data is to explore some of the many Web-based citizen-science programs out there. They are designed to give users a fun experience and inspire them to seek out more ways to work with scientific data. Zooniverse hosted one of the first—and is still home to some of the best—projects, and it has citizen-science programs in far more disciplines than astronomy, although it always has several space-related ones running at any given time. All you need to get started is an internet connection and a Web browser. The programs have well-defined tasks for participants, and Zooniverse provides all the training and tutorials you need to help with its projects.

Anyone from children to senior citizens can participate and make real contributions; no one needs advanced astrophysics knowledge to understand what they are looking for. You can help as little or as much as you want, and some "citizens" have been coauthors on journal articles that have emerged from their work. Zooniverse has ready-made activities for classrooms, or you can design your own. For some teachers, though, the activities may seem too polished and may not be enough of a challenge for students, so they won't absorb the deeper meaning of the tasks they are doing.

Many programs let you use astronomy data for canned labs. Hands-On Universe was one of the first programs to bring astronomy data into the classroom, back in the 1990s. Participants could use existing data in a structured framework or request new data from a network of participating telescopes around the world. (It was the source of the lab I used in the Adler teacher workshop mentioned in the introduction.) The program's activities—many still available online—enabled learners to determine angular sizes, explore the cosmological distance ladder, find supernovae, and construct Hertzsprung–Russell diagrams. Those activities still provide ways for novice learners to start working with real data, take their own measurements, and begin to understand why and how astronomers make quantitative measurements of celestial objects.

TWO STUDENTS, who were part of a 2023 NITARP team, compare results for the detailed calculations that they made to plot spectral energy distributions.

A more recent example of a program working with real data is the Vera C. Rubin Observatory education group. Although the observatory hasn't seen first light yet, the education group has already prepared several online lessons, using placeholder data, for classroom use now. When the data start flowing in earnest, real Rubin Observatory data will be added to those online lessons, in sufficient quantity so that all students in even large classes will get "their own" data to use. The lessons explore asteroids, cosmology, the solar system, and dying stars, and more are planned. Once again, just a Web browser is needed. Importantly, the educational group has worked to put the infrastructure in place to allow teachers to run (and easily grade) labs for large groups of students, in which each student, or each pair or trio of students, is working with different data and will come up with different answers. The group has also provided connections to the relevant Next Generation Science Standards.[2]

Student-collected data

Even the canned labs that use real data don't usually require more than a Web browser. More advanced programs, however, assume a more advanced level of understanding. Some programs facilitate students collecting their own data by granting remote access to a telescope.

One such program, which is almost as old as Hands-On Universe, is the MicroObservatory Robotic Telescope Network, operated by the Center for Astrophysics|Harvard & Smithsonian. Its most recent effort enables students to search for exoplanets. It provides the scaffolding needed to help learners contribute their real data to the archive and combine their own data with others' to find the exoplanet transit signal. That would not be an easy task done on their own because a planet transit represents at most a few percent drop in the light from the star. Conducting photometry that precise is challenging, especially for beginners. Within the scaffolding established by the program, however, participants can do a straightforward analysis using just a Web browser.

A more open-ended example is the Skynet Robotic Telescope Network, out of the University of North Carolina (UNC) at Chapel Hill. It was established for research purposes, but a substantial fraction of the observing time goes for educational purposes, such as undergraduate classes at UNC-Chapel Hill and other schools, Skynet University, Skynet Junior Scholars, IDATA (Innovators Developing Accessible Tools for Astronomy), and other curricula for college and advanced high school classes. Participants can request data from the telescope network as part of a class or program. And the software developed by UNC-Chapel Hill, known as Afterglow, enables that request plus the analysis required to, for example, create three-color images with optical images alone or in conjunction with archival IR images, perform photometry, and analyze the results. The scaffolding provided by the curriculum builds skills that could be leveraged into independent research projects for science fairs.

More astronomy for your classroom

I have collected all the programs I know about that get data into the hands of middle and high school teachers and students here: https://nitarp.ipac.caltech.edu/page/other_epo_programs.

The list is long. Not everything on it is still running. All involve access to real data, but they populate a rather large parameter space—the literal spectrum of light, the spectrum of interaction with professional researchers, and the spectrum of using someone else's data access and management software or developing your own. Some allow for lots of interaction with the people who run the program, and some depend on your ability to read the documentation they've provided and learn on your own. That is the case especially for the programs that are no longer actively running but keep their materials available on their website.

Some have geographic restrictions, but many do not. The list focuses on precollege students specifically because myriad opportunities are readily available to college students doing research. If you know of more programs for precollege teachers or students that I have missed, please let me know and I will add them.

There are also various ways to introduce real data or research into the classroom, aside from working with either via any of the methods described here.

NASA's Astronomy Picture of the Day (https://apod.nasa.gov/apod/astropix.html) uploads a new image daily with a brief explanation of what it is and why it matters. The site also has resources specifically for educators. Simply having the site up while students assemble in the classroom can spark conversations about current events or results.

The site Astrobites (https://astrobites.org) takes one article per day and summarizes it in language suitable for upper-level high school and undergraduate-level readers. The authors are current graduate students. They focus on new research, historical work, or other issues of importance to the community. They also write summaries of American Astronomical Society (AAS) meetings during the meetings, including press events.

You can follow the AAS press office (https://aas.org/press) on social media or subscribe via email to get copies of astronomy-related press releases, which are written for the general public. The press releases about articles in AAS journals, which are now all open access, include links. The Smithsonian Astrophysical Observatory/NASA Astrophysics Data System (https://ui.adsabs.harvard.edu/) includes the AAS journal articles among its 15 million publications records. The text of nearly all astrophysics papers can be found on the arXiv preprint server's astrophysics section (https://arxiv.org/archive/astro-ph).

Those kinds of programs are not just limited to the optical regime. NASA's Radio Jove Project asks participants to build their own radio telescope and then obtain observations of Jupiter, the Sun, and our galaxy. You can contribute your data to or explore data from the project's archive.

To take your own data and contribute meaningfully to a larger effort, you need to have a relatively deep understanding of what you are doing. Recently, because of progress in software, a high level of data quality can be achieved with only a Web browser. But even then, introducing young students to scientific research doesn't stop there.

Educating the educators with NITARP

Few current programs get real data into the hands of teachers and their students while also allowing them to participate in actual research. Such a program asks the most from its participants because it requires them to have sustained, deep interactions with the program organizers and a substantial understanding of the astronomy and astrophysics relevant to the project. But the interactions with organizers can fundamentally change the way that participants view science. One such program, which I helped found, started in 2005: the NASA/IPAC (formerly known as the Infrared Processing and Analysis Center) Teacher Archive Research Program, or NITARP. It partners small groups of mostly high school educators with a research astronomer for a 13-month-long (from January to January), authentic astronomy research project.

Who we work with

The "T" in NITARP stands for "teachers." If we work with only students, then our influence in a school ends when the students graduate. But if we work with educators, we influence the several hundred students they teach not just that one year but every year for the rest of their career. It is hard to beat the multiplicative effect. We know through our educators that we also reach other educators with whom they work in their school, district, and even state. Our participating educators are largely physics and astronomy teachers, but they also include chemistry, math, computer science, biology, and Earth-sciences teachers; museum educators; and other nonclassroom educators. Our participants—140 educators between 2005 and 2023—are from 42 states in the US and counting. Approximately 75% are high school classroom educators, and roughly 75% of them work in public schools.

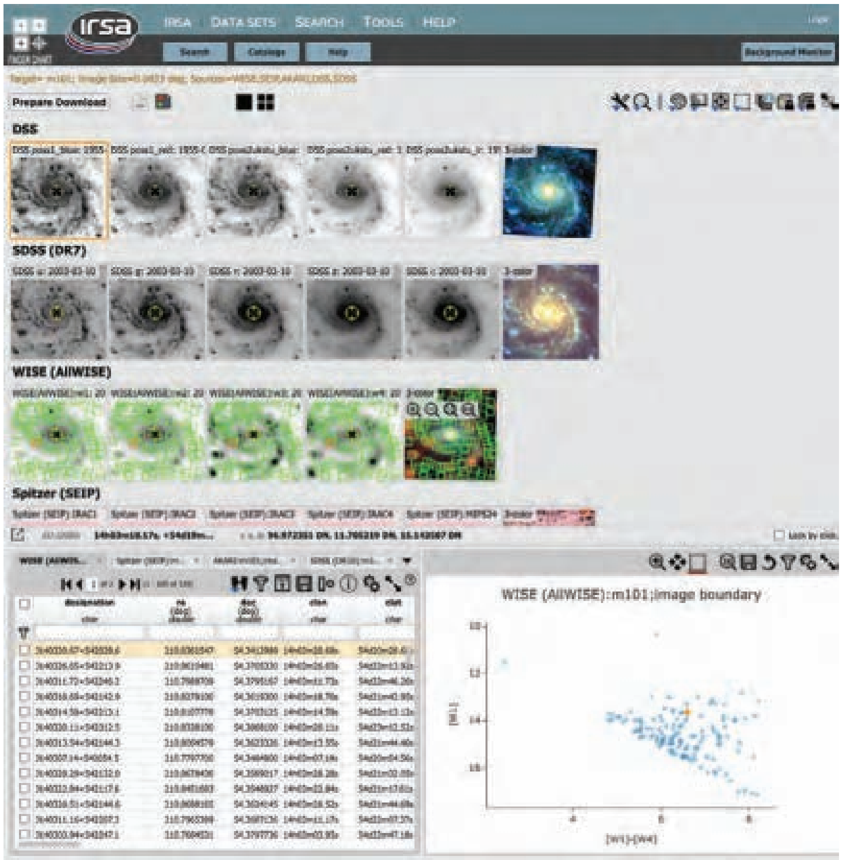
We don't systematically track our educators after they finish working with us, but we do have anecdotal evidence of the effect of NITARP on their students. One became the first African American woman to graduate with a degree in astrophysics from the University of Wisconsin–Madison, which is significant because there are so few Black women in the field. An autistic student selected by his teacher to participate wasn't initially interested in school at all; his family wrote to us because they credit NITARP not only with his graduating high school but with his starting community college. Sometimes the program has unexpected results; for example, a student from a wealthy community saw others going to school to become only medical doctors and lawyers, but as a result of NITARP, he was astounded to discover that those weren't his only choices for a career.

Research scope

The "I" in NITARP stands for "IPAC" and the "A" for "archive." All the NITARP teams work with archival data housed at Caltech-IPAC. Fortunately, a staggering amount of data is available, so there is no shortage of data to be found or science to be done. We do not ask teams to do advanced work—projects are comparable to what one might give a summer undergraduate. But the projects are also authentic science research, and as such, the teams don't always find what they set out to find. All the completed proposals and posters are available on the NITARP website, although coverage for some of the earliest years is spotty. As is the case for all conference posters (and summer research projects) everywhere, not all of them become journal articles. But some NITARP projects do,[3–5] and those are posted on the website.

To kick off the year, we give a NITARP workshop so teams can meet and start learning about their project. That happens just before the educators attend a January conference of the American Astronomical Society (AAS) to experience the largest astronomy meeting in the world and see how scientific discourse is conducted. Afterward, the teams go home and start working remotely. They write a proposal, which is peer reviewed by both educators and astronomers, and respond to the review. Final proposals are posted on the NITARP website.

The teams work remotely through the spring. In the summer, they visit us at Caltech; each educator can bring up to four students. Although the four-day trip may seem like a routine research trip for a professional scientist, it is often the first time that most participants have encountered days full of intense research. Students work and learn side by side with the educators on the trips. The teams make substantial progress on their project during the visit, but they rarely complete everything; they go home and keep working remotely. The abstracts for the January AAS meetings are typically due in early October, and each team makes at least two posters, one on the work's science and one on its education aspects. They then go to the January AAS meeting to present their results.



RESEARCH-GRADE ASTRONOMY DATA ON THE WEB. This screenshot shows the search results for the Messier 101 galaxy; they were created using a tool called Finder Chart, provided by NASA/IPAC Infrared Science Archive. Each image covers the same region on the sky; each row is from a different survey. The color image at the end of each row is constructed of that row's images. The colored points overlaid on the image are from the corresponding catalog and are shown as a table in the lower left and as a plot in the lower right. The image overlays, the table, and the plot are all interactive.

Influencing educators

There is high demand among secondary school educators for teacher experiences like those provided by NITARP. Five times as many educators apply to the program as there are spots available. That oversubscription ratio is par for the course in astronomy, and actually much better than what astronomers face when applying for time on some telescopes or for grants. But in education, specifically professional development, that is far from typical. Not only does NITARP have that kind of oversubscription, our alumni often raise their own money to return to the AAS meetings after their initial research project ends, continue to work with us on extensions of research projects, and find ways to get the research better integrated into their classrooms.

We have been doing this in one form or another since 2005, and so we have shaken out the bugs. We have begun to explore more rigorously the influence of our program on our educators.[6–9] The tendrils of NITARP's influence extend far beyond what we ever expected, and probably beyond what we know about. At least 14% of alumni say NITARP was life-changing and has shaped how they think about science and scientists and how they teach science. The sustained, long-term interaction among the participants—both scientists and educators—helps foster relationships between NITARP alumni beyond what NITARP can facilitate in a single year.

NITARP has had a significant role in the career changes of 10 alumni that we know of. Some have been promoted in their district so that they can influence science education at a higher level and with broader impact. Most importantly, 60% of alumni say NITARP inspired them to improve the way they include science in their classroom. Those changes are attributed by the educators to their NITARP experience.

Not much education research has been done on the effect that programs like those discussed here have had on teachers who participate in them. What research exists tantalizingly suggests that having teachers simply take part in authentic

There are many ways to incorporate astronomical data into a classroom at a range of expertise levels.

- Caltech-IPAC: https://www.ipac.caltech.edu/
- Hands-On Universe: http://handsonuniverse.org/usa/activities
- IDATA: https://idataproject.org
- IRSA: https://irsa.ipac.caltech.edu/frontpage
- MicroObservatory Robotic Telescope Network: https://mo-www.cfa.harvard.edu/MicroObservatory
- NASA Exoplanet Archive: https://exoplanetarchive.ipac.caltech.edu/
- NASA/IPAC Extragalactic Database: https://ned.ipac.caltech.edu
- NITARP: https://nitarp.ipac.caltech.edu
- Radio Jove Project: https://radiojove.gsfc.nasa.gov
- Skynet Robotic Telescope Network, Junior Scholars, and University: https://skynet.unc.edu, https://skynetjuniorscholars.org, https://skynet.unc.edu/introastro
- Skynet-Based Curricula: https://www.danreichart.com/curricula
- Vera C. Rubin Observatory education group: https://rubinobservatory.org/education
- Zooniverse: https://zooniverse.org, https://classroom.zooniverse.org/#

research improves student achievement.[10] Additionally, when educators are engaged longer in a program, it significantly increases the benefits they receive from it.[11] Other work explores how teachers' research experiences change their understanding of the nature of science, with a specific focus on astronomy.[12] Recent papers attempt to collect the literature and identify gaps in knowledge about how research experiences affect teachers and students.[13]

Improving access through archives

It used to be that astronomers went to a telescope, obtained their data, and took them home. (I remember once refusing to send computer data tapes through the x-ray detector at the airport on my way home.) We now don't have to go to a telescope to collect data, but even when we do physically visit an observatory, we still download them from an archive when we get home to reduce on our own computers. It is, however, getting to the point that the amount of data is too large to download at once. Archives are, right now and in real time, adapting to the reality that at least some analyses will need to happen within the archive, and some will be done at home.

The change is more equitable—a century ago, astronomy could be done only by those whose institution had a telescope. Starting about 40 years ago, publicly accessible telescopes were established in the US, so an institution didn't necessarily have to own a telescope for its scientists to do astronomy. On around that same time scale, the first publicly accessible astronomy archives were made available, and many more have since come online. People at smaller institutes or in smaller or economically marginalized countries can still do astronomy. Soon archives will have substantial publicly accessible computing resources and tools that can help all users—professionals and laypeople—perform computationally intensive analyses.

So many research-grade data sets are currently available on the Web for anyone to access. All the telescopes funded by US government money have a mandate to make their data publicly available. NASA has many more telescopes than just the headline-grabbing *Hubble Space Telescope* and *James Webb Space Telescope*, and all those data are free for the asking. NASA's telescopes make their data available in several archives. I work for the NASA/IPAC Infrared Science Archive, or IRSA. We must make our tools and data easy to access for all astronomers, including the emeritus professor who can barely read his email and the summer student embarking on her first research project. Because we have to meet the needs of all of them, we will also probably be able to meet your needs, although you will have to become familiar with IRSA tools and astronomy jargon (and you need Chrome or Firefox as your browser).

IRSA houses the original data from many of NASA's long-wavelength missions, and it has quite a bit of highly processed data that are ready to use for science. IRSA provides access to more than 700 billion astronomical measurements, including all-sky coverage in 24 bands. In total, IRSA hosts more than 8 petabytes of data from at least 18 projects. For approximately 15% of refereed journal articles in astrophysics annually, the authors used data curated at IRSA. And it is just one of eight NASA astrophysics archives—not to mention NASA's planetary archives and the other US and international astronomy archives. There are so many archives out there to explore.

I suggest starting with IRSA, though, in no small part because once you master our tools, you can access many of the rest of the world's astronomy archives via the Virtual Observatory protocols. Many tutorial videos introduce users to IRSA's Web-based tools, including ideas for how to use the tools for educational purposes. You can also write your own code to access IRSA's tools via application programming interfaces.

IRSA is just one of several archives at Caltech-IPAC; others include the NASA Exoplanet Archive and the NASA/IPAC Extragalactic Database. Both are focused on specific scientific goals and curate their data and tools accordingly.

With all those data available, there are countless possibilities for projects to introduce your students to the world of astronomy. Who knows what futures may be unlocked by including modern scientific research early in education.

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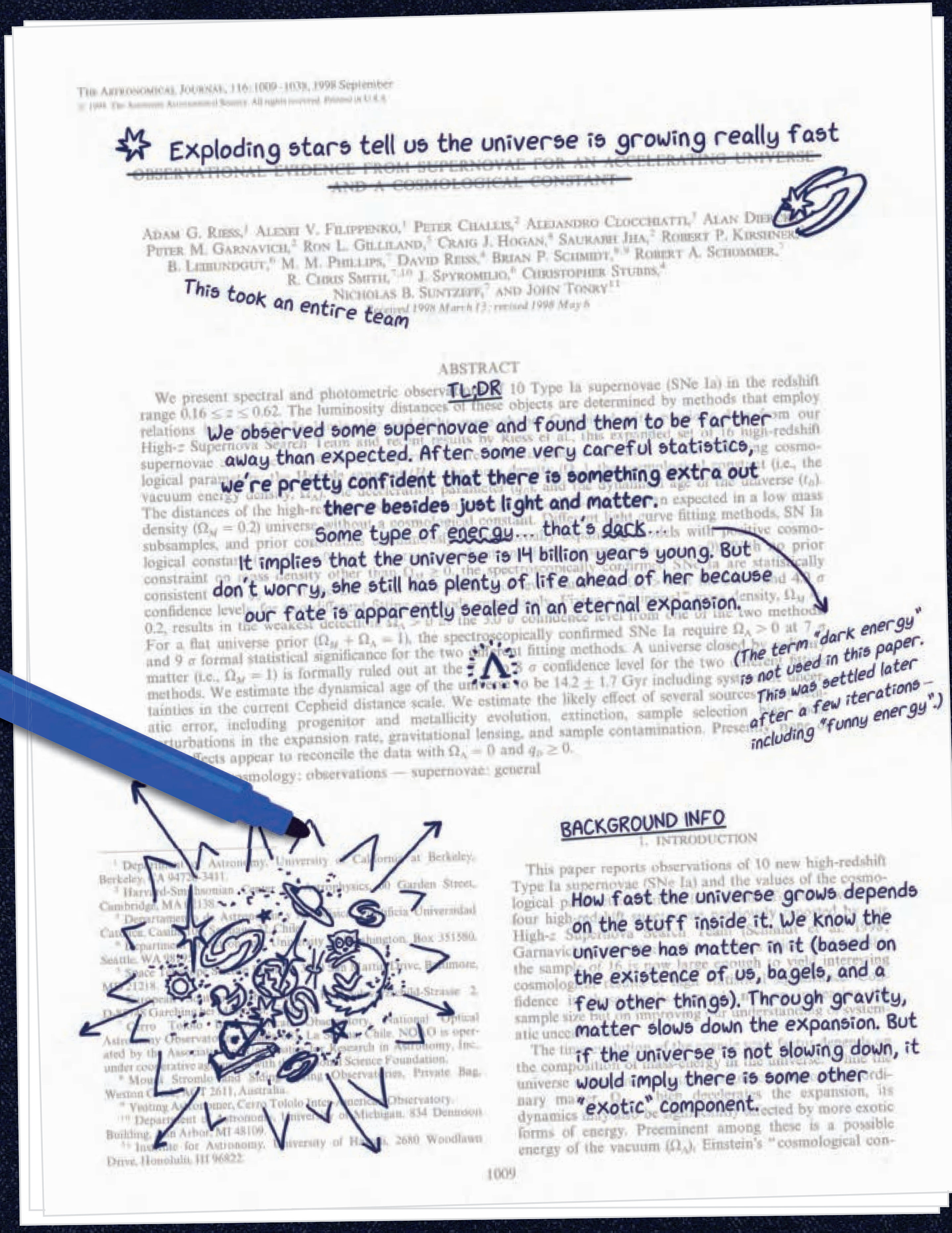
Claire Lamman is a cosmologist, science communicator, and PhD student at the Center for Astrophysics | Harvard & Smithsonian in Cambridge, Massachusetts.

Translating scientific papers for the public

Claire Lamman

Eager to make your research accessible to a general audience without glossing over all the effort that has gone into your work? Try creating "doodle summaries" of your papers.

Communicating scientific results to a general audience is difficult. Communicating the tangle of methods and analysis that support neatly packaged results, not to mention the uncertainties, is even more challenging. To lift the hood on the process, I suggest a method to explain science in the most direct way possible: by doodling annotations on scientific papers.


The Astronomical Journal, 116:1009–1038, 1998 September

Exploding stars tell us the universe is growing really fast

~~OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT~~

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Dier[...] Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2] B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7] R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4] Nicholas B. Suntzeff,[7] and John Tonry[11]

This took an entire team

Received 1998 March 13; revised 1998 May 6

ABSTRACT

TL;DR

We observed some supernovae and found them to be farther away than expected. After some very careful statistics, we're pretty confident that there is something extra out there besides just light and matter.

Some type of energy... that's dark...

It implies that the universe is 14 billion years young. But don't worry, she still has plenty of life ahead of her because our fate is apparently sealed in an eternal expansion.

(The term "dark energy" is not used in this paper. This was settled later after a few iterations—including "funny energy".)

Λ

BACKGROUND INFO

1. INTRODUCTION

How fast the universe grows depends on the stuff inside it. We know the universe has matter in it (based on the existence of us, bagels, and a few other things). Through gravity, matter slows down the expansion. But if the universe is not slowing down, it would imply there is some other "exotic" component.

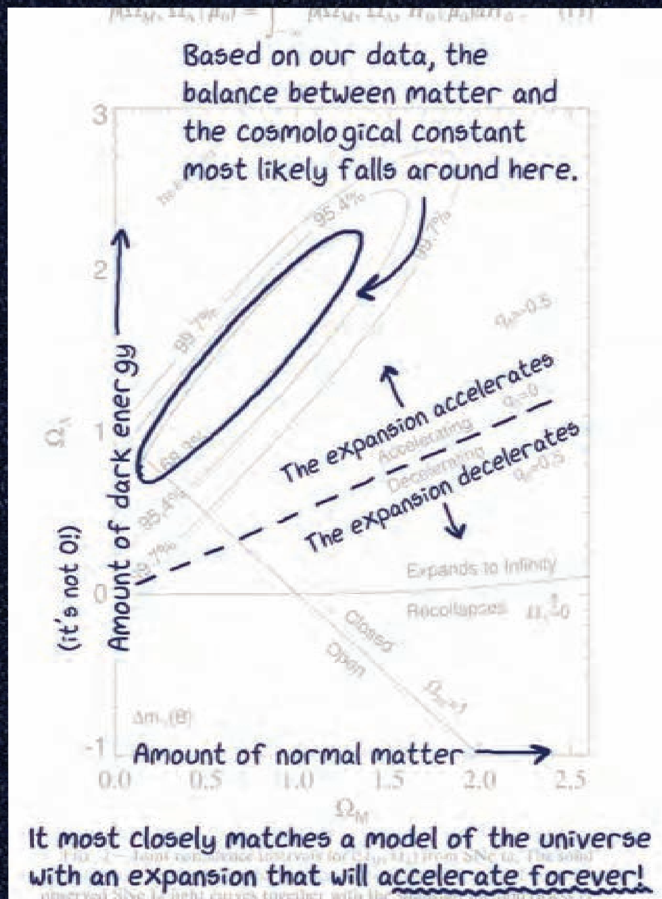
1009

The idea came about two years ago when my mom mentioned that she was excited to read a recent paper of mine. The research was on a subtle systematic effect in cosmological surveys, a topic specific enough that I worried even people in my field would have difficulty understanding it. I wanted to explain the paper in a way that gave my mom a real idea of my work and what went into it.

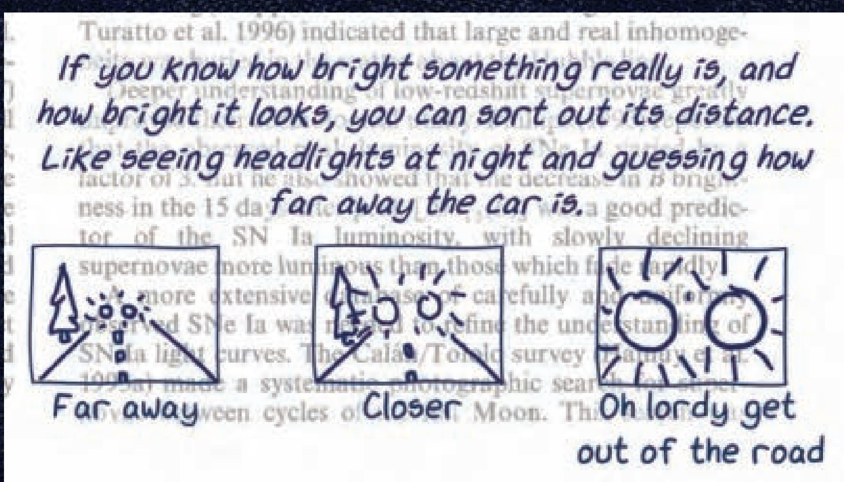
The result was a doodle summary. I placed the PDF version of my paper in PowerPoint and annotated it with text, diagrams, cartoons, and more. I linked to the annotation on the paper's arXiv.org page and received a large, positive reception from other scientists. Several researchers have since made similar summaries of their papers.

The annotated-paper approach is helpful for describing research to colleagues, sharing the content of papers with undergraduates, and explaining to the public what goes into scientific research. It's also a clean way to visually communicate the most important ideas from a paper's plots and tables. I've found that general audiences are often surprised by how much work underlies a single result and how much of a paper scientists may devote to describing all the reasons they may be wrong.

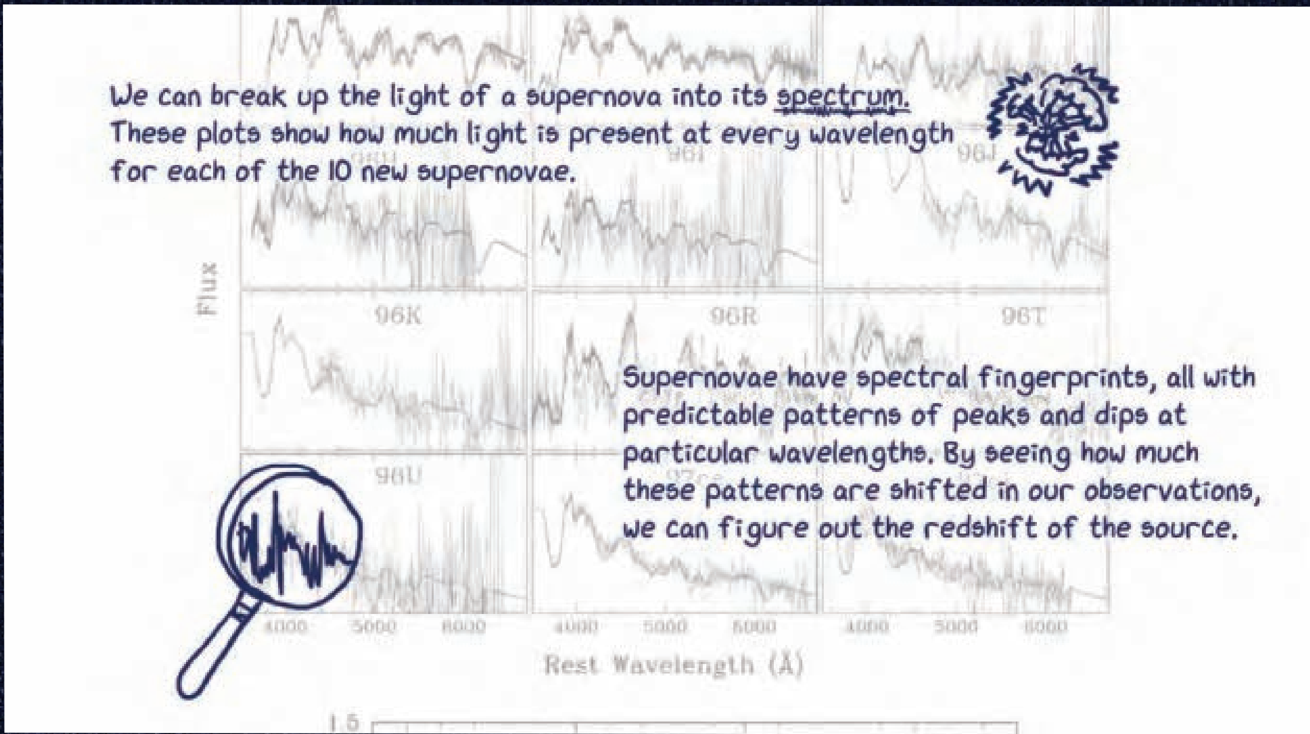
The doodles in this feature annotate the ground-



APPEARING HALFWAY through the 30-page manuscript, this is the pivotal graph that demonstrates the universe's accelerating expansion. A doodle summary highlights a plot's takeaways while de-emphasizing the jargon and symbols. Axis labels are simplified, and helpful context is included.



THIS SET OF CARTOONS is a fun way to illustrate a basic principle for using supernovae at various distances to measure the universe's expansion.



DATA TABLES AND FIGURES are ideal places to explain the background science that underlies the research. In this example, annotations overlaying the spectra of several supernovae explain spectroscopy and how it is used to measure the redshift of cosmic objects.

breaking 1998 *Astronomical Journal* paper by Adam Riess and colleagues, who used observations of supernovae to make a compelling case that the expansion of the universe is accelerating. Combined with research by Saul Perlmutter and collaborators that was published in the *Astrophysical Journal* several months later, it is the most consequential result in modern cosmology, one that was recognized with the 2011 Nobel Prize in Physics.

The snippets illustrate some of what I did to summarize the paper by Riess and colleagues. I encourage readers to try to do something similar with their own research papers.

The annotations use the xkcd font, CC BY-NC 3.0, https://github.com/ipython/xkcd-font. PT

For the full annotation, visit https://physicstoday.org/doodle.

AS MANY RESEARCHERS do in their papers, Adam Riess and colleagues use a significant portion of their manuscript—in this case, 7 of their 30 pages—to address all the possible ways they may be wrong. A doodle summary simplifies each of those factors without glossing over them, like many popular-science articles do. For researchers summarizing their own work, it's a valuable opportunity to describe how much effort goes into producing a piece of peer-reviewed research.

JENNIFER SIEBEN

Wave turbulence equations have been used to describe the physics of ocean waves.

To rule the waves

The modern understanding of wave turbulence began in 1929 when Rudolf Peierls published his thesis work on heat conduction in crystals. Subsequent developments in the 1960s centered on the study of surface waves, and eventually, Vladimir Zakharov and his coworkers developed the theory into a sharply honed tool to describe weakly interacting waves. Their work focused on deriving an equation for the nonlinear evolution of the wave spectrum. It resembles the Boltzmann equation—commonly associated with gaseousphysics—which led to the name: wave kinetic equation.

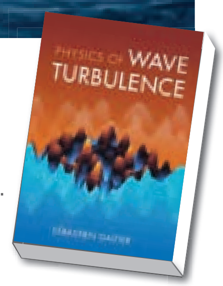
Today wave turbulence theory is applied to a diverse range of systems, including internal gravity waves, which are important for the long-term dynamics of the ocean. The variety of questions that the theory can answer—made possible by comparing the kinetic equation to simulations—has led to new experimental designs and testable predictions. At the same time, mathematical progress has placed the formal derivation of the kinetic equation onto much firmer ground, decisively so for idealized systems, such as the nonlinear Schrödinger equation.

Until now, students and researchers who wanted to learn about the field had to choose between *Kolmogorov Spectra of Turbulence I: Wave Turbulence*, by Zakharov, Victor S. L'vov, and Gregory Falkovich and published in 1992, or *Wave Turbulence*, by Sergey Nazarenko and published in 2011. The latest option is the welcome addition of *Physics of Wave Turbulence* by Sébastien Galtier. The author has a long track record in the field, including original applications to plasma systems, magnetohydrodynamics, rotating and stratified waves, compressible waves, and the solar wind. It is clear from reading the book that the subject is close to the author's heart.

Physics of Wave Turbulence

Sébastien Galtier

Cambridge U. Press, 2022. $74.99 (hardback)



For a newcomer to the field of wave turbulence, the formal derivation of the kinetic equation may appear austere and rigid. The process starts from the governing equations in a particular form—typically that of a canonical Hamiltonian partial differential equation system—and then follows a long sequence of partially convincing, partially mystical steps to finally arrive at the kinetic equation. Galtier's book offers a different take by stressing how multiple time scales can be used in the derivation. Although the idea is not new, and the outcome of the derivation is the same, the fresh perspective should help new readers.

Physics of Wave Turbulence starts with a general introduction to turbulent systems and then chronicles the basic theory of hydrodynamic turbulence, or turbulence in fluid systems. It is mostly standard material, but Galtier adds fresh touches here and there, such as a novel derivation of the famous energy spectra found in turbulent systems—the first derivation of which was accomplished by Andrei Kolmogorov in 1941.

Spectral cascades, which describe the nonlinear flow of energy from large forcing scales to small dissipation scales, are introduced, and the dramatic differences between 2D and 3D spectral cascades are described. In a nutshell, in 3D the energy flows naturally to very small scales, but in 2D, a counterintuitive inverse cascade moves energy to larger scales. For subtle reasons, the large-scale turbulence in the atmosphere and in oceans behaves much like a peculiar 2D system, so inverse cascades are, in fact, crucially important in practice.

After presenting that material, Galtier introduces wave turbulence, which he discusses through a sequence of increasingly complex physical models. The models simulate capillary waves, which travel at the interface between two fluids, and the so-called inertial wave turbulence, which is hydrodynamic turbulence in rapidly rotating containers. Interestingly, some of those systems exhibit inverse cascades as well.

Further applications include Alfvén waves relevant to incompressible magnetohydrodynamic systems, compressible plasma waves, and, finally, gravitational waves; a chapter on possible scenarios of the primordial universe discusses gravitational wave applications. The numerous exercises, integrated in the main text with solutions provided at the end of the book, are a welcome feature.

Like its two siblings, and despite the large amount of mathematics contained in it, *Physics of Wave Turbulence* is true to its name, so certain specific questions that may vex mathematicians are not addressed. I don't think that it a weakness of the new book, which is an excellent addition to the textbook literature on the subject. It simply means that a useful mathematical treatment of wave turbulence remains to be written.

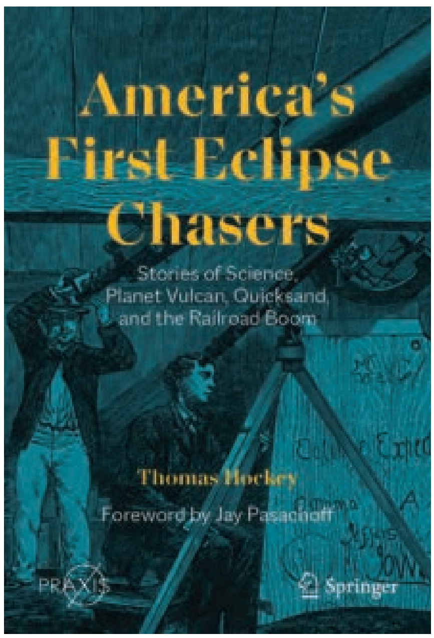
Oliver Bühler
New York University
New York City

NEW BOOKS & MEDIA

America's First Eclipse Chasers

Stories of Science, Planet Vulcan, Quicksand, and the Railroad Boom

Thomas Hockey
Springer, 2023. $37.99 (paper)



In advance of the next total solar eclipse, happening in April 2024, astronomer Thomas Hockey looks back at the first ever to occur over the continental US during the nation's history—that of 7 August 1869. That eclipse was notable in many ways, according to Hockey. First and foremost, it spawned the first large-scale astronomical expeditions in the US, which were aided in part by the number and portability of new astronomical instruments and the burgeoning US railway system. It also marked the first use of photography to capture scientifically useful images of the Sun. In *America's First Eclipse Chasers*, Hockey argues that the eclipse expeditions were the "biggest simultaneous scientific enterprise in the United States up to that time."

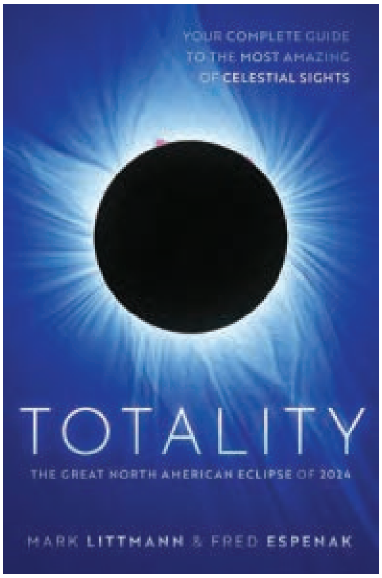
—CC

Totality

The Great North American Eclipse of 2024

Mark Littmann and Fred Espenak
Oxford U. Press, 2024. $18.95 (paper)

In preparation for the April total solar eclipse, science writer Mark Littmann and astrophysicist Fred Espenak have produced this timely guide to what could be "the biggest outdoor spectator event in American history." Not only do they provide information and advice about viewing the eclipse on 8 April 2024, but they also discuss the different types of eclipses and the science behind them, eclipses throughout history, the experiences of early eclipse chasers, firsthand accounts of what it's like to observe an eclipse, and guidelines for safely photographing the phenomenon. Illustrated with 220 photos, diagrams, tables, and maps, *Totality* is a handy reference for would-be eclipse chasers. —CC



Monarch

Legacy of Monsters

Chris Black and Matt Fraction, creators
Apple TV+, 2023

When *Godzilla* first reached the big screen in 1954, it was an unsubtle analogue for the destructive force of the atomic bomb and how difficult it would be to control. Set in the same universe as the 2014 film reboot, the new Apple TV+ series *Monarch: Legacy of Monsters* tackles a different message: After they discover a problem, how active should scientists be in fixing or controlling it? In the show, the organization Monarch, which was designed to investigate and protect civilians from giant monsters, evolves into something its founders didn't expect: a passive observer to monster attacks. That message seems particularly timely given debates within the scientific community on how to tackle climate change. Fiction can be a good introduction into discussing real-world problems with students, and hopefully that will be *Monarch*'s legacy. —PKG PT

NEW PRODUCTS

Focus on test, measurement, quantum metrology, and analytical equipment

The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. PHYSICS TODAY can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new product submissions to ptpub@aip.org.

Andreas Mandelis

Photon-counting pixel detector

Dectris has renewed its Pilatus photon-counting pixel detector for synchrotrons; the instruments can also approach synchrotron-like performance in scientific instruments in the laboratory. The Pilatus4 detectors combine speed and a large active area. They feature a maximum count rate of 10^7 photons/s/pixel. For highly efficient detection over a wide energy range, they are available with silicon or cadmium telluride sensors. With up to four independent energy thresholds that can be recorded simultaneously, the detectors enable suppression of disturbing fluorescence and higher harmonic radiation. Because of their 150 μm pixel size and sharp, single-pixel point-spread function, they deliver ultrahigh spatial resolution, ensuring independent counting of neighboring pixels. The Pilatus4 detectors offer high resolution from the lowest flux valleys to the highest data peaks. For high data quality, they are noise free and stable. Thanks to the Simplon application programming interface, integration is fast and reliable. ***Dectris USA Inc****, 1500 Walnut St, Ste 1630, Philadelphia, PA 19102, www.dectris.com*

Mixed-signal oscilloscope

The 4 Series B mixed-signal oscilloscope (MSO) now available from Tektronix offers increased processing power for quicker analysis and data transfer speed. It features the same signal fidelity as the earlier 4 Series, with bandwidths from 200 MHz to 1.5 GHz, real-time sampling at 6.25 gigasamples/s, and up to 16-bit vertical resolution. It also includes the same touch user interface, but with an upgraded processor system that is twice as responsive and speeds up remote operation. The 4 Series B MSO is available with up to six input channels, making it suitable for three-phase power analysis. The company's Spectrum View capability provides multichannel spectrum analysis in sync with time-domain waveforms. The 4 Series B MSO enhances time to answer on more than 25 serial decode packages for interchip, automotive, power, and aerospace bus applications, among others. It also speeds up the algorithms and plotting used in existing analysis packages for power-supply measurements, motor-drive analysis, and double-pulse testing. ***Tektronix Inc****, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

Hardware-accelerated oscilloscope

Keysight has expanded its Infiniium oscilloscope portfolio by adding the MXR B-Series. It offers built-in automated debugging tools, including zone triggering, fault detection, real-time spectrum analysis, and a 50 MHz waveform generator. The hardware-accelerated analysis reduces test time by automating fault detection, design-compliance testing, power-integrity analysis, decoding of more than 50 serial protocols, and mask testing on all channels simultaneously. According to the company, with a low noise floor, high effective number of bits, and very low system jitter, the Infiniium MXR B-Series delivers high performance on all eight channels, preserving signal integrity and providing the maximum resolution possible. It captures important events in the signal with an update rate of greater than 200 000 waveforms/s, a fast sample rate of 16 gigasamples/s, and a bandwidth up to 6 GHz that does not decrease with channel usage. ***Keysight Technologies****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Ultracompact transducers

According to Thyracont, its new miniaturized vacuum transducers unite digital and analog and offer an optimal price–performance ratio. The PTL and PTR models are suitable for use in turbomolecular pumps and spectrometers and in analytical applications, particularly when space is limited. With their piezo/Pirani combination sensor, the transducers measure in a wide range in rough and fine vacuum with high resolution and accuracy. Both models measure absolute pressure in a range from 2000 mbar to 5×10^{-5} mbar. The PTR model also measures relative pressure in a range from −1060 mbar to +1200 mbar. A fast response time of 5 ms and excellent resolution enable stable, short-cycled, efficient production processes. The optimized individual temperature compensation provides excellent accuracy and steady measuring values. The devices also allow precise digital readjustment to atmospheric or zero pressure, programming of the gas-type correction factor, and retrieval of various parameters for preventive maintenance. ***Thyracont Vacuum Instruments GmbH****, Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*

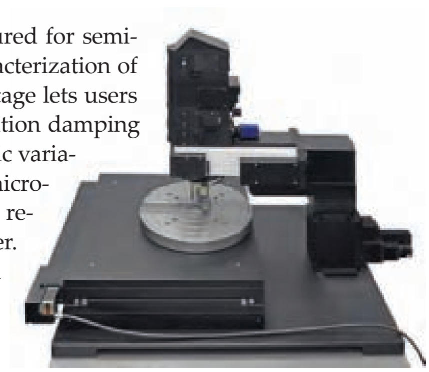
Fast eight-channel oscilloscope

Rohde & Schwarz has introduced an eight-channel oscilloscope, which the company says shows more of a signal's activity in the time and the frequency domains than other oscilloscopes: The R&S MXO 5 is the first eight-channel oscilloscope with 4.5×10^6 acquisitions/s and 18×10^6 waveforms/s across multiple channels. Users performing power- and signal-integrity measurements and logic and bus-protocol debugging can capture intricate signal details and infrequent events with high precision. Digital triggering on all eight channels enables accurate isolation of small signal anomalies. The R&S MXO 5 series's capability of 45 000 FFTs/s provides optimal spectrum-signal viewing, particularly for EMI and harmonic testing. Standard simultaneous acquisition memory of 500 Mpoints (megasamples) across all eight channels allows for extensive data capture. The R&S MXO 5 oscilloscopes are also available with four channels; models with 100, 200, 350, and 500 MHz and 1 and 2 GHz bandwidths are offered. ***Rohde & Schwarz GmbH & Co KG****, Mühldorfstraße 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Environmentally friendly gas analyzer

Hiden Analytical now offers an enhanced and more environmentally friendly version of its quantitative gas analysis system for academic and industrial research. The QGA 2.0 is constructed with sustainable materials that can easily be easily recycled and offers energy-efficient operation. It weighs less than 30 kg and has a footprint 42% smaller than the original QGA's. Optimized for continuous analysis of gases and vapors in near-atmospheric pressures, the QGA 2.0 can perform 1000 measurements/s and detection from 100 ppb to 100%. Its response time is less than 300 ms with less than 0.5% error at 1 ppm. The QGA 2.0 has a seven-decade dynamic range. It can discriminate isobaric mass interferences, such as NH_3^+ and OH^+, at m/z17. Various inlet accessories and configurations are available for sampling from ambient pressures to ones as high as 30 bar. Applications of the QGA 2.0 include carbon capture, analysis of hydrogen and high-purity gas, environmental monitoring, fuel-cell studies, and thermal analysis–mass spectrometry. ***Hiden Analytical Inc****, 37699 Schoolcraft Rd, Livonia, MI 48150, www.hidenanalytical.com*

Raman imaging for wafer characterization



Oxford Instruments WITec has unveiled a confocal Raman-imaging microscope configured for semiconductor R&D. The alpha300 Semiconductor Edition is designed to accelerate the characterization of chemical composition, crystal quality, strain, and doping. Its extended-range scanning stage lets users inspect wafers up to 300 mm in size and acquire large-area Raman images. Active vibration damping and optical profilometer-driven active focus stabilization help compensate for topographic variation during measurements over large areas or long acquisition times. Fully automated microscope components permit the implementation of standard measurement procedures and remote operation. The system includes a highly sensitive, on-axis, lens-based spectrometer. The excitation-wavelength-optimized spectrometer features a thermoelectrically cooled scientific-grade spectroscopic CCD camera and delivers ultrahigh throughput. The latest WITec software, Suite Six, facilitates data acquisition and advanced postprocessing. ***WITec Instruments Corp****, 300 Baker Ave, Ste 150, Concord, MA 01742, https://raman.oxinst.com*

FTIR metrology for semiconductor applications

Semilab has announced a new generation of its rapid, noncontact, and nondestructive Fourier-transform IR spectroscopy (FTIR) metrology system, EIR. The enhanced EIR system delivers high accuracy, efficiency, and uptime to a wide variety of applications in the semiconductor industry, including epitaxial layer thickness determination for silicon and silicon carbide, chemometric analysis of thin films, and interstitial oxygen and carbon measurements in bulk silicon. The EIR optics now provide higher throughput without sacrificing long-term stability. Semilab can retrofit existing systems with an improved detector and longer service life. In addition to the hardware improvements, new software features include improved analysis methods for silicon carbide, a wafer-sorting capability, and a new system-health-check module. The EIR product line can support different levels of factory automation and can be integrated into existing facilities and new facilities that maintain the latest standards. ***Semilab USA LLC****, 12415 Telecom Dr, Tampa, FL 33637, https://semilab.com* PT

Michael Marder is a professor at the Center for Nonlinear Dynamics at the University of Texas at Austin.

From cracks to atoms and back again

Michael Marder

For the past 200 years, fracture has been at the cutting edge of science.

Something usually seems real only when we can detect it with our own senses. The famous 1972 photograph of Earth as a blue marble rising above the Moon is a dramatic case in point. It makes our planet appear round in a vivid way unseen before.

What, then, can we make of atoms, which will always be too small to see with ordinary visible light? The speculation that matter is made of atoms goes back millennia to Lucretius's *De Rerum Natura* (*On the Nature of Things*). Compelling scientific evidence is not that old, but it does go back centuries to an unexpected corner of physics—the fracture of solids—where the influence of atoms, if not the atoms themselves, is visible.

Cleaving crystals

Fracture is the process by which external forces break a solid object into pieces. It can happen in any solid but is most suggestive as it occurs in crystals. Many of those types of stones have translucent optical properties that make them precious or semiprecious and produce fractures with flat surfaces. Jewelers can cleave them into appealing symmetrical shapes, a process that happens because crystal faces form only at specific angles to one another.

The cleaving occurs only along invisible natural joints inherent in each crystal. In the late 18th and early 19th centuries, the French mineralogist René Just Haüy imagined that crystals are built from vast numbers of identical cells, from which the faces emerge as stepped surfaces. For example, a surface that goes sideways two units and upward one unit will form an angle 26.5° above the horizontal, as shown in the left panel of the figure.

Haüy's struggle to explain fracture opened a winding intellectual path that led over the next hundred years to an understanding of matter as being composed of atoms. But scientists were slow to take up the question of how to explain fracture itself. The first modern study was published in 1920 by the British engineer Alan Arnold Griffith, who examined the strength of glass fibers as their diameters decreased. The stress needed to break them increased the thinner the fibers became, and from that trend he deduced that the breaking stress is inversely related to the depth of the largest crack on their surface. He also focused on the fact that energy is required to break the bonds when cleaving a surface, and a crack can advance only if energy is available.

Griffith had annoyed his superiors at the Royal Aircraft Establishment at Farnborough by doing experiments on glass rather than on aluminum and other practical materials that would help ensure the safety of airplanes. He also had the misfortune of setting his laboratory on fire one night. Thus he was ordered to stop work on glass after 1920.

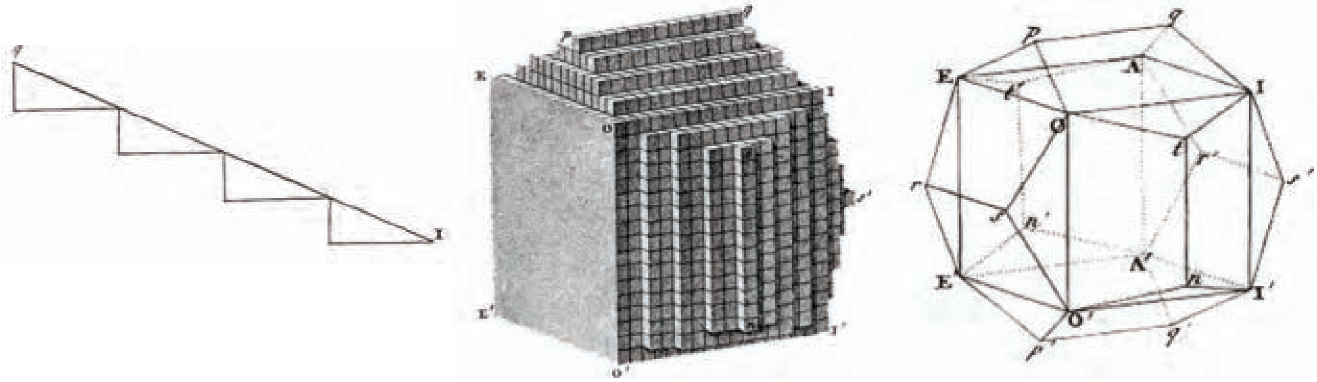
Three decades later the UK's de Havilland Aircraft Company produced the world's first commercial jetliner, and not long into service several planes fell mysteriously from the sky. The line of investigation Griffith had begun was exactly what was needed to understand why, but by the time the significance of his work became fully apparent, leadership in both the study of fracture and the manufacture of jet airplanes had moved across the Atlantic Ocean to the US.

Concentrated stress

The key person at the forefront of fracture science in the US was George Rankin Irwin. Although his first degree was in English, he obtained a PhD in physics from the University of Illinois in 1937 and then went to work at the US Naval Research Laboratory. During World War II, he began to investigate the fracture of steel. The US Navy needed additional insight into the topic to build armor and to stop the phenomenon of new all-welded ships, which had been built in haste for the war, sometimes cracking in half on launch.

Starting in 1948 Irwin developed a new theory for fracture. He began with Griffith's observation that cracks need energy to move and then asked how that energy flowed. When a cracked solid is under tension, energy stored inside it spontaneously runs to the crack tip, like water in a pool rushing into a drain. At the tip, it creates a stress concentration that is strong and sharp enough to cut atoms apart. The detailed mathematical theory shows that in the vicinity of the crack tip, stress and strain fields take a universal form, rising as one over the square root of distance to the crack tip. The coefficient of that universal stress configuration is called the stress intensity factor.

In brittle crystals, severe material disruption ahead of the crack is limited to distances of a few atomic lengths. If you notch a silicon crystal along one of its planes and pull on it



RENÉ JUST HAÜY'S DRAWINGS from 1822 explain how the angles in a crystal are made from many identical cells. The sketch at left shows how steps relate to an angled surface. The center panel presents cells forming a stepped surface on a crystal, and the right one shows a wire frame outline of a macroscopic crystal. (Adapted from R. J. Haüy, *Traité de cristallographie, suivi d'une application des principes de cette science* [. . .] *Atlas*, ["Treatise on crystallography, followed by an application of the principles of this science . . . Atlas"], 1822.)

gently, it will come apart. The slight resistance you feel is literally a line of atomic bonds unzipping. The great brittleness makes silicon a poor structural material.

To make structures that endure, builders tend to use materials such as steel, in which an approaching crack tip is disruptive over much larger length scales than in silicon. Driving the crack tip forward in steel requires the metal to flow plastically—that is, to move in a way that's more fluidlike than solidlike.

At macroscopic scales, however, Irwin's theory for energy transfer still applies; the stress falls off away from the crack tip in universal inverse-square-root fashion. That way of thinking about fracture unified the study of cracks of many types and paved the way to the engineering study of fracture mechanics.

It took until the 1960s for Irwin's view of fracture to be accepted: At a 1997 symposium dedicated to Irwin, H. P. Rossmanith said, "It was necessary to overcome a substantial amount of unsympathetic reaction." Paul Paris, a graduate student at Lehigh University in the late 1950s, studied Irwin's theories while working in the summer at Boeing, just in time for the engineers there to develop its first civilian jet. Paris proposed a now-classic theory on how cracks creep forward in vibrating structures. It was rejected so many times from journals that Paris eventually placed it in a student engineering magazine. By the end of the 1960s, the whole theory of fracture was placed on a rigorous footing by James Rice—working at Brown University at the time—and other applied mathematicians, and it became a standard part of the engineering curriculum.

A contemporary perspective

Fracture continues to present physics with fascinating scientific questions. Two examples of recent work make the case. Yael Klein and Eran Sharon conducted experiments in thin strips of gel at the Hebrew University of Jerusalem. Because the material is both brittle and floppy, they found that it can undergo a transition that had never before been observed. Sometimes a seed crack runs through the strip. But under slightly different stress conditions, the strip responds by buckling out of the plane instead.

Studying that transition has led scientists to create a new theoretical framework in which to view cracks, where a crack is represented as a line distribution of internal buckling (see my article with Robert Deegan and Eran Sharon, Physics Today, February 2007, page 33). The new theory complements the more familiar representation of a crack as a line distribution of stress monopoles called dislocations.

Irwin's theory postulates that cracks cannot run faster than sound because its speed sets fundamental limits on transporting energy to the crack tip. One can solve the problem of crack motion in crystals analytically, however, and those calculations say that cracks can travel at any speed set by the strain level, so long as the strain is big enough and the crack is not allowed to branch. Supersonic cracks in tension were seen 20 years ago in rubber, but it was thought a peculiarity of that material. New experiments by Jay Fineberg and collaborators in brittle gels are also finding cracks that travel faster than sound. They are trailed by Mach cones at a speed set by the strain level, giving evidence that the predictions from calculations in crystals are correct.

Fracture is a phenomenon that helped atoms seem real, for the fracture of crystals could not be explained without them. Fracture links the macroscopic and microscopic worlds like no other mechanical process, and in doing so continually leads—literally—to scientific breakthroughs.

Additional resources

► J. E. Gordon, *The New Science of Strong Materials, or Why You Don't Fall Through the Floor*, 2nd ed., Princeton U. Press (1976).
► A. A. Griffith, "The phenomena of rupture and flow in solids," *Philos. Trans. R. Soc. Lond. Ser. A* **221**, 163 (1920).
► Y. Klein, E. Sharon, "Buckling-fracture transition and the geometrical charge of a crack," *Phys. Rev. Lett.* **127**, 105501 (2021).
► P. J. Petersan et al., "Cracks in rubber under tension exceed the shear wave speed," *Phys. Rev. Lett.* **93**, 015504 (2004).
► M. Wang, S. Shi, J. Fineberg, "Tensile cracks can shatter classical speed limits," *Science* **381,** 415 (2023).
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BACK SCATTER

Twisted liquid crystal

Chiral structures—those that can't be superimposed on their mirror images—typically form from chiral molecules. Achiral building blocks can be assembled into a chiral whole, but it is challenging to engineer the requisite spontaneous symmetry breaking. Among the systems in which the phenomenon has been observed are rod-shaped liquid crystals: When confined in a small, curved space, some of the molecules, which usually orient themselves in parallel, will twist to minimize their free energy. To date, however, only liquid crystals in static environments have had their symmetry broken.

Qing Zhang, Weiqiang Wang, and their collaborators have now discovered a distinct, dynamic pathway to mirror-symmetry breaking. They drove a liquid crystal through a 40 mm microfluidic cell a few microns thick. At a low flow rate of 0.25 μL/min, the liquid crystal twisted itself into a chiral structure, which takes the form of the striped pattern shown here when viewed through crossed polarizers. The characteristic spacing between the stripes is determined by the two types of torque acting on the liquid crystal. The researchers found that by manipulating the flow velocity and cell thickness, they can tune the spacing, which could prove useful in creating macroscopic chiral structures. (Q. Zhang et al., *Nat. Commun.* **15**, 7, 2024; image submitted by Qing Zhang and Irmgard Bischofberger/MIT.) —AL

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