PHYSICS TODAY

November 2019 • volume 72, number 11

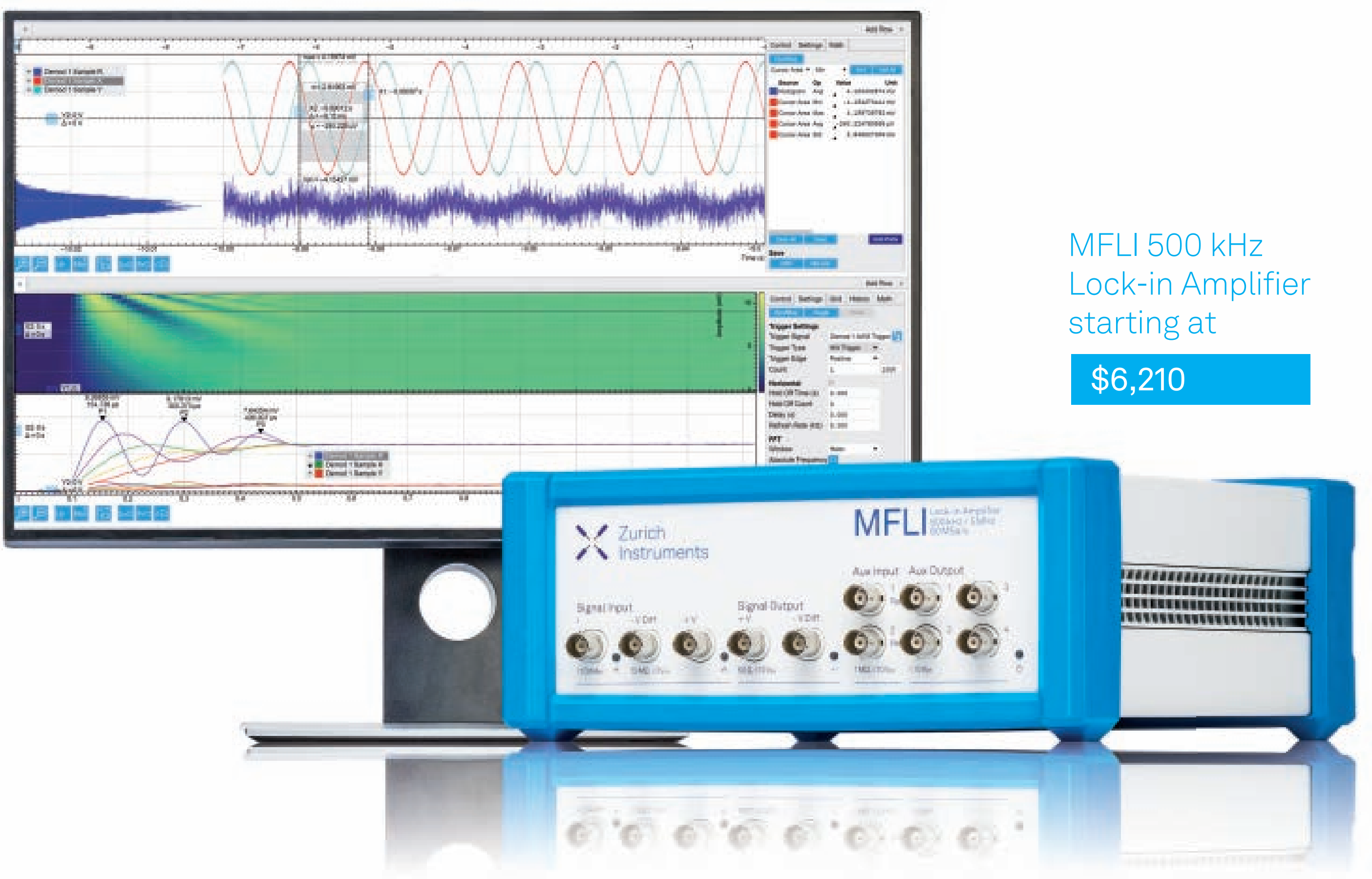
A publication of the American Institute of Physics

FLUID DYNAMICS of wildfires

New family of superconductors

US–China collaborations under strain

Odd behavior of chiral fluids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PHYSICS TODAY

November 2019 | volume 72 number 11

FEATURES

ON THE COVER: Tens of thousands of wildfires scorch the continental US each year. Predicting their behavior is complicated by their interactions with local winds and with variations in vegetation and terrain. For more on the two-way feedback between a wildfire and the air flow in and around it, turn to the Quick Study on **page 70**. (Image by iStock.com/noscoo.)

Recently on PHYSICS TODAY ONLINE

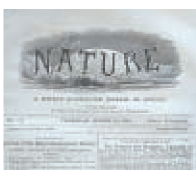
www.physicstoday.org

WIKIMEDIA COMMONS

▶ Math vs. science

In two recent columns, Physics Today's Johanna Miller compares science, which relies on inductive reasoning, with the deductive endeavor of mathematics. She illustrates the difference by exploring Euclid's infamous parallel postulate. You can find all of Miller's columns at physicstoday.org.

physicstoday.org/Nov2019a



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▶ Physics in *Nature*

The journal *Nature* turns 150 years old this month. Physics Today editor Melinda Baldwin, who wrote a book about *Nature*'s history, explores how physicists' desire to publish in the journal has waxed and waned over the years. Its editors and the competition—notably *Physical Review Letters*—have played a big role.

physicstoday.org/Nov2019b

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▶ Teach energy first?

Most intro college physics courses begin with kinematics and Newton's laws. The University of Kansas (KU) tried teaching energy and conservation laws first in some classes. The KU faculty reports the energy-first students gained more conceptual understanding than did those in force-first classes.

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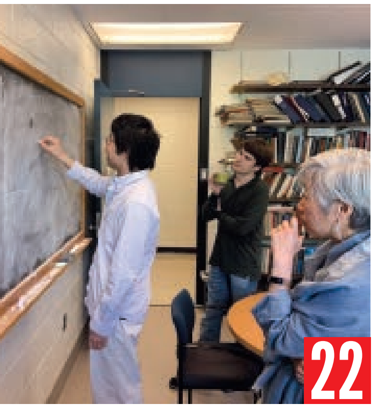

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Declare your motivations

Charles Day

For PHYSICS TODAY's November 2002 issue (page 22), I wrote a news story entitled "Why do lobsters change color when cooked?" The unlikely topic readily qualified for coverage. Obtaining the answer to the title's question entailed using three innovative crystallographic techniques. Astaxanthin, the pigment responsible for the color of the lobster's exoskeleton, is biophysically interesting and biomedically significant.

Still, my fellow editors and I determined that the story should be short. Accordingly, I left out much of what I'd learned from my interviewees about why anyone would want to know how lobsters change from greenish black to orangey red when boiled or broiled.

The story begins with George Wald (1906–97), who was awarded a share of the 1967 Nobel Prize in Physiology or Medicine for identifying the molecules that underlie mammalian vision, a protein called opsin wrapped around a light-absorbing form of vitamin A called retinal. Rhodopsins, as the combinations of opsin and retinal are known, span the membranes of photoreceptor cells, which means their tops and bottoms penetrate the cells' aqueous interior and exterior while their middles abut the membranes' oily interior. Being both hydrophilic and hydrophobic makes opsins and other membrane proteins hard to crystallize. Unable to make crystals of opsin, Wald turned instead to crustacyanin, the pigment in lobster shell.

In my news story I mentioned Wald's interest in crustacyanin, but not his motivation. Although crustacyanin resembles rhodopsin in that it consists of a protein wrapper and astaxanthin, a vitamin-A-like molecule, it is not a membrane protein. Wald hoped to gain insights into the structure of rhodopsin by studying crustacyanin. Perhaps because crustacyanin is surrounded by calcium carbonate, it, too, defied crystallization. Naomi Chayen, who was part of the team that solved the lobster color-change problem, eventually succeeded. Her technique involved topping a solution of crustacyanin with a layer of kerosene thin enough to allow the crustacyanin solution to slowly concentrate via evaporation and crystallize. The crystallization took four months.

Chayen's research is directed at coaxing recalcitrant molecules to crystallize. Her motivation was self-evident. By contrast, the motivations of the paper's lead author, Michele Cianci, surprised me. Crustacyanin is stable in water. It could form the basis of a new class of biocompatible blue food colorants, he told me. Astaxanthin is a potent antioxidant, but the molecule's symmetry deprives it of polarity and therefore the ability to dissolve in water. Wrap a drug like astaxanthin in a protein cage like crustacyanin's, and you could have a way to deliver it through the bloodstream to where it might be needed.

I've just reread the original paper[1] that Cianci, Chayen, and their collaborators published in 2002. It contained even less about their motivations than my short news story did. For comparison, I looked up my own research papers. All of them have coauthors. I picked one that I could remember writing mostly by myself (my coauthor, Christine Done, and I contributed equally to the research).[2] The paper was about x-ray bursters, the neutron star analogs of classical novae that Koji Mukai and Jennifer Sokoloski review in their feature article on page 38.

Material from the neutron star's companion, a low-mass star, makes its way through an accretion disk to the neutron star surface. When enough material has accumulated, it undergoes a thermonuclear detonation, which x-ray detectors record as a sudden and fleeting burst of x rays. My idea was that some of the x rays from the peak of the burst would reflect off the accretion disk and into an observer's line of sight. Spectral features imprinted on the reflected radiation would be challenging to detect given the strong contrast with the direct radiation. But, I hypothesized, the burst's precipitous drop in intensity and the finite speed of light would together ensure that the reflected light from the peak would arrive at a detector at the same time as direct light from the now dimmer burst. Done and I simulated that process to see if absorption lines could be detected.

Alas, I didn't say much about why detecting the lines was interesting or important. Yes, I wrote that it could help discriminate between two emission mechanisms. But why was that interesting or important? I realize now that I had presumed readers would already agree with me that the behavior of plasma under extreme gravity is worth investigating.

If you write papers, please consider declaring your motivations. Your readers will be grateful and interested, even if your motivation is pure curiosity. You'll also earn the gratitude of science journalists at PHYSICS TODAY and elsewhere who read your papers.

References

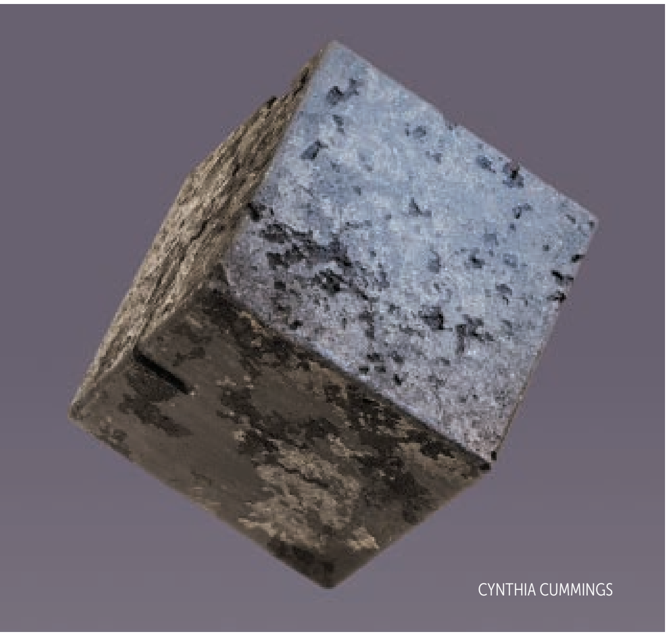
1. M. Cianci et al., *Proc. Natl. Acad. Sci. USA* **99**, 9795 (2002).
2. C. S. R. Day, C. Done, *Mon. Not. R. Astron. Soc.* **253**, 35P (1991). PT

A note on German uranium stores

Timothy Koeth and Miriam Hiebert's fascinating detective work on the German uranium cubes (PHYSICS TODAY, May 2019, page 36) sheds new light on Germany's often overlooked wartime nuclear program.

The article prompted me to look at an aspect of the German work I did not consider while revising my *History and Science of the Manhattan Project*, Koeth and Hiebert's reference 1: How did the amount of uranium the Germans had available compare with that used in Enrico Fermi's Chicago Pile-1 (CP-1)? It turns out that the Germans had much less: Their 1064 natural uranium cubes would have had a total mass of about 2.5 tons; CP-1 incorporated about 5.6 tons of pure uranium metal and 37 tons of uranium oxide.

Much of Germany's uranium was in the form of plates, most of which probably ended up in the US at Oak Ridge or Hanford. In his study of the German program, Mark Walker comments that Werner Heisenberg's "large-scale" plate experiment, the B-VII pile, was planned to contain 3 tons of uranium metal, much less than a single full fuel load of the Oak Ridge X-10 reactor at about 106 tons or of one of the Hanford reactors at 255 tons.[1] The cylinder for the German cube-based pile would have held about 1.7 tons of heavy-water moderator (less, if the volume of the cubes is accounted for); CP-1 boasted nearly 350 tons of graphite moderator. Those numbers drive home the immense difference in scale between the German and Allied programs.



CYNTHIA CUMMINGS

A striking aspect of all the German pile experiments was their lack of any control mechanisms. We—and they—can be grateful that they did not succeed. I hope that Koeth and Hiebert's article will lead to the discovery of more uranium cubes.

Reference

1. M. Walker, *German National Socialism and the Quest for Nuclear Power, 1939–1949*, Cambridge U. Press (1989), p. 85.

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Cautions on physics master's degree

On the benefits of a physics master's degree, I must add two cautions to Toni Feder's story (PHYSICS TODAY, April 2019, page 22). After I completed my MS in physics in 1991 from a public university in North Carolina, my undergraduate alma mater, also a public university in the state, refused to recognize my MS as preparation for further graduate work. The physics department's then graduate admissions officer told me to not even bother applying because I would not be accepted. Of the universities I approached in my home state, only one, a private institution, said it would recognize my MS degree.

A master's in physics is good preparation for teaching. However, too many institutions, even community colleges where teaching is ostensibly the focus, list a PhD as either a preferred or required credential for introductory, undergraduate, nonresearch teaching positions. They favor applicants with PhDs over those with their master's despite the accreditation guidelines, at least in my part of the country, being identical for community colleges and four-year colleges and universities. That bias exists because institutions either don't fully understand the accreditation guidelines or willfully ignore them to boast in marketing materials about having so many PhD faculty members. The job market is flooded with PhD recipients whose training is in research, not teaching. Master's degree holders need to be aware of that problem.

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Comedy of errors boosted 1920s Einstein mania

In his tale of how Albert Einstein became a celebrity in the US (PHYSICS TODAY, April 2019, page 38), Paul Halpern claims that "during a time of xenophobia, globally minded Americans gravitated to him as an outspoken foreign scientist expressing an international outlook." In support of that claim, Halpern cites Marshall Missner's paper[1]

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> **As Einstein himself described it, he served for display as “a prize-winning ox.”**

“Why Einstein became famous in America.” But he grossly misreads it. Missner’s paper mentions that Einstein’s friendly demeanor and sloppy attire momentarily allayed American xenophobia, but nowhere does it say anything about globally minded Americans and an international outlook.

Missner reveals that the mania generated by Einstein’s 1921 visit was triggered by a comedy of errors. The purpose of the visit was a Zionist fundraising campaign organized by Chaim Weizmann. Einstein was invited to join as a poster child, to be seen on stage with Weizmann but not heard. As Einstein himself described it, he served for display as “a prize-winning ox.”

When Weizmann and Einstein’s ship arrived at its New York pier, thousands of enthusiastic Zionists came to cheer, and they again showed up two days later at City Hall. But they came for Weizmann, not for Einstein. The Yiddish newspapers reported that accurately and mentioned Einstein only briefly. But the English-language newspapers misperceived the celebrations as being in honor of Einstein. The mistaken Anglo narrative quickly gained dominance in the press, and even the Yiddish newspapers then gave more attention to Einstein. With his witticisms, his pipe, his violin, and his casual attire, Einstein made for much better copy than the earnest and formally attired Weizmann. And a superstar was born.

I thank Professor Missner for reviewing this letter and confirming my interpretation of his paper.

Reference

1. M. Missner, *Soc. Stud. Sci.* **15**, 267 (1985).

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Prep for chemistry PhD is as hard as for physics

In his commentary in the March 2019 issue of PHYSICS TODAY (page 10), Sankar Das Sarma opined that “all-encompassing expertise merely to begin their thesis research is essentially unthinkable in chemistry.”

I received my PhD in organic chemistry from the University of Massachusetts Amherst in 1977. Before students could begin their research in that department, they had to demonstrate graduate-level expertise in all areas of chemistry, even those seemingly unrelated to their research. Thus I also had to pass courses for inorganic and physical chemistry.

To become a PhD candidate, one then had to pass six, hours-long cumulative exams given periodically over two years. The questions depended on the specialty of the professor who set the exam. If that was photochemistry, then the questions were all about that field; likewise for physical organic chemistry, natural products, and so on. Moreover, questions were sometimes written in German; if you could not understand them, then too bad for you! Most students taking one of those exams did not receive a passing grade.

I am left to conclude either that educational standards in the physical sciences have declined considerably over the years or that Das Sarma's institution is an anomaly.

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A US physicist and the military draft

Charles Day's editorial "Drafting physicists" in the January 2019 issue of PHYSICS TODAY (page 8) brought to mind my own interesting interactions with the military during my early years.

I was too young for the Korean War but still had to register for the draft at age 18. After that I had various deferments, mostly for education. My graduate schooling was supported by a National Defense Education Act fellowship, which gave priority to students who planned on becoming college professors.

I received a PhD in 1966 and accepted a position as an assistant professor of physics at the South Dakota School of Mines and Technology in Rapid City. That employment ended my educational deferment. In a few months I received notice to report for the physical, in Sioux Falls. I remember taking the long overnight bus ride from Rapid City with some of the students I'd taught at the School of Mines.

The head of the physics department was dismayed that I would have to leave my position. He encouraged me to appeal and wrote a letter for me to present to the draft board, stating how hard it was for him to recruit a college physics professor and how much the nation needed to educate upcoming physicists and engineers. Apparently, the members of the draft board were persuaded: I did not have to report for duty.

Years later, at my high school reunion for the class of 1955 in Huntley, Wyoming, I noticed others had red carnations in their buttonholes. I asked the woman at the desk about them, thinking that I might be getting one. I was told that carnations were for those who served in the armed forces. Not until then had I felt even a twinge of regret for not serving my country. It did not matter what accomplishments I may have had as a physicist; in fact, no one there knew—or cared—what those might be. Without a carnation, I was labeled.

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THE DEPARTMENT OF PHYSICS AT THE UNIVERSITY OF WISCONSIN IS HIRING IN THE FOLLOWING FIVE AREAS:

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To ensure full consideration, please apply by December 1, 2019. However, the positions will remain open and applications may be considered until the positions are filled.

An inexpensive crystal makes a fine quantum time machine

To understand the intricacies of thermodynamics in the quantum regime, it helps to be able to turn back the clock.

The laws of classical mechanics are time reversible. A movie of a particle, or even a few colliding particles, looks equally realistic when played forward or backward. An ensemble of many particles, on the other hand, is characterized by a parameter, entropy, that always increases with time. As the system progresses toward thermal equilibrium, it loses all memory of its initial nonequilibrium state.

Classical physics ultimately derives from quantum physics, because all real-world classical systems are composed of quantum systems. Classical many-body ensembles thermalize, so quantum ones seemingly must do the same. But the nature of quantum time evolution—described mathematically by a so-called unitary operator—means that quantum information can never be created or destroyed and quantum systems can never lose their memory of their previous states.

To resolve that apparent paradox and gain a deeper understanding of what "thermalization" means in the quantum world, researchers seek to study how information propagates across a nonequilibrium quantum system. To do that, they need methods, whether theoretical or experimental, to link the single-body and many-body scales with enough detail and control to coherently track the evolution of quantum states and enough interacting particles to exhibit meaningful thermodynamics. That's hard.

Now MIT's Paola Cappellaro and colleagues are finding that a way forward might lie in a surprisingly simple experimental setup: an inexpensive natural crystal—bought from a jewelry vendor on eBay for $10—and an ordinary NMR machine.[1,2] The crystalline material, called fluorapatite, has long been recognized as a useful model of one-dimensional spin chains.[3] Its fluorine atoms, depicted in red in figure 1, are arranged into long, well-separated columns that are interrupted only by rare crystal defects.

Fluorine's only stable isotope is the spin-½, NMR-active ^{19}F. Using the techniques of solid-state NMR (see the article by Clare Grey and Robert Tycko, PHYSICS TODAY, September 2009, page 44), Cappellaro and colleagues are able not only to manipulate and probe the ^{19}F spins but also to tinker with the effective Hamiltonian that describes how the spins evolve. One of the things they can do, importantly, is create opposite-signed versions of the same Hamiltonian, which effectively propagates the system forward and backward in time.

The ability to rewind time lets the researchers construct an experimental measure, based on a so-called out-of-time-order (OTO) commutator, of how thoroughly their spin system has explored its space of available quantum states. Roughly speaking, a system in thermal equilibrium is equally likely to be found anywhere in that space, and a system out of equilibrium is not. By measuring OTO commutators, Cappellaro and colleagues can see how swiftly and completely their spin chains approach equilibrium—and get a glimpse of the peculiar ways in which quantum systems sometimes fail to thermalize.

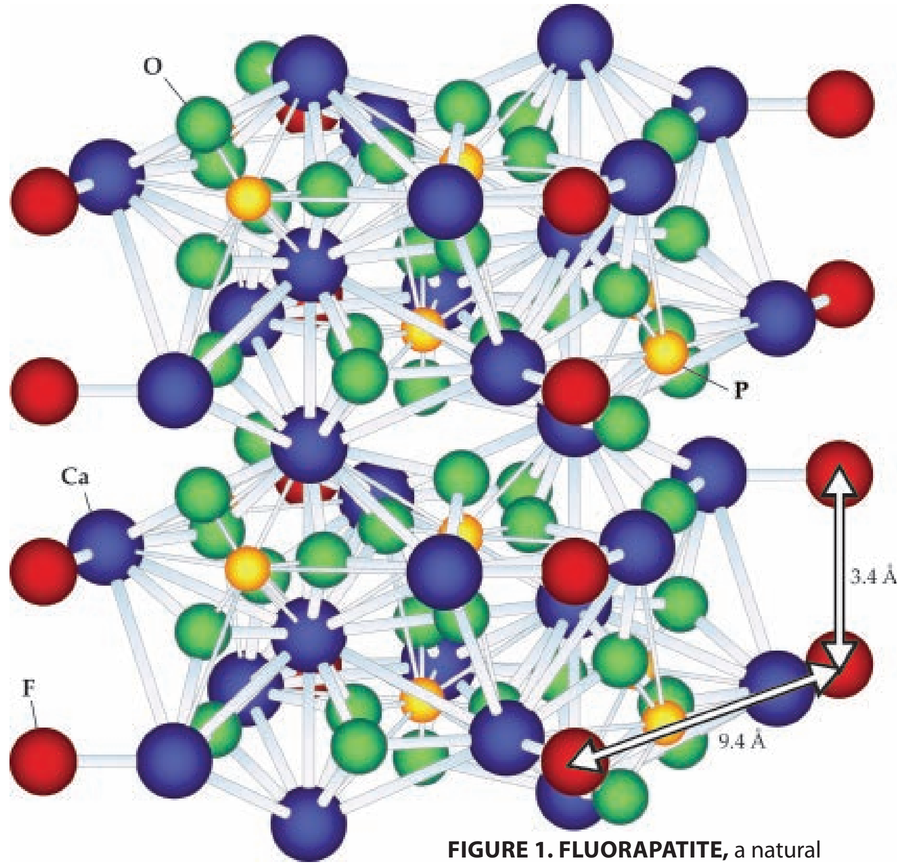

FIGURE 1. FLUORAPATITE, a natural material sometimes used as an inexpensive gemstone, is a compound of calcium (blue), phosphorus (yellow), oxygen (green), and fluorine (red). Because the distance between F atoms in the horizontal plane is nearly three times the distance between nearest-neighbor F atoms in the vertical direction, the F atoms thus approximate an ensemble of one-dimensional spin chains. (Adapted from W. Zhang et al., *Phys. Rev. A* **80**, 052323, 2009.)

Out of order

An OTO commutator is similar to the familiar commutators used in quantum mechanics to quantify the compatibility, or lack thereof, of pairs of observables. For example, a particle's position x and

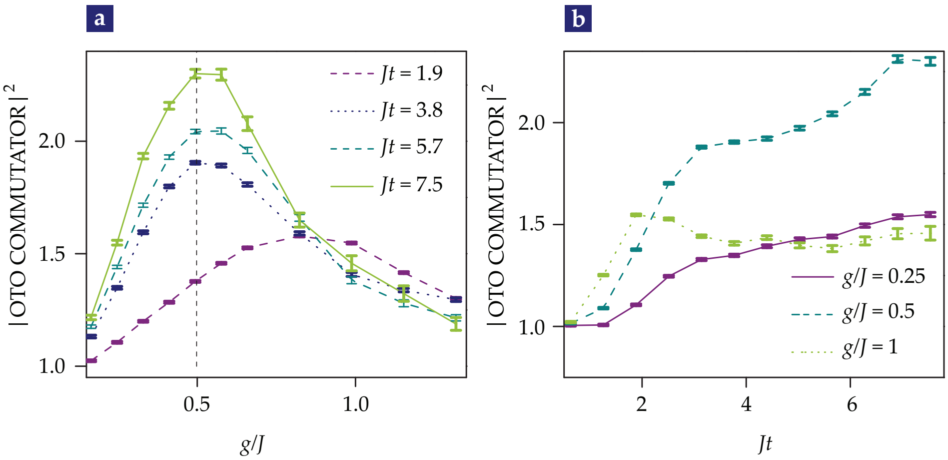

FIGURE 2. PRETHERMALIZATION DYNAMICS emerges in the fluorapatite spin system when the effective magnetic field g is relatively large compared with the spin–spin interaction strength J. **(a)** When g/J is 0.5 or less, the magnitude of an out-of-time-order (OTO) commutator grows steadily with time t, the hallmark of quantum thermalization. For larger values of g/J, the OTO commutator stops growing when the system reaches a prethermal steady state. **(b)** Here, the data are plotted as a function of t rather than g. (Adapted from ref. 2.)

momentum p aren't simultaneously measurable; if both are measured, the order of the measurements matters. Mathematically speaking, the operators representing those quantities don't commute: $px - xp$ is nonzero.

The "out of time order" part comes from considering the two operators at different times—say, x at time 0 and p at time t. The OTO commutator asks, Does measuring $x(0)$ then $p(t)$ give the same results as measuring $p(t)$ then $x(0)$? That is, does $p(t)x(0) - x(0)p(t)$ equal zero?

From a theoretical perspective, there's nothing paradoxical about the idea of making a later measurement first and an earlier measurement second. One need only write down a factor of $e^{iHt/\hbar}$ in between their two operators, where H is the system's Hamiltonian, to represent the rewinding of time. (Forward-propagating time, in contrast, is represented by $e^{-iHt/\hbar}$.)

Experimentally, it's also possible, at least in principle, to turn back the clock on any quantum system. A quantum state has a unique backward trajectory in time, just as it has a unique forward trajectory, and an ably chosen combination of measurements can extract information about what that trajectory is. Despite their apparent oddity, OTO commutators can make both mathematical and physical sense.

OTO commutators are especially useful as probes of how information spreads throughout a quantum system—as, for example, an initially localized spin excitation diffuses along a chain of interacting spins. At first, the states of spins at opposite ends of the chain are compatible observables—measuring one has no effect on the other. But as time goes by and each spin's influence spreads across the system, distant spins become progressively more entangled, and their OTO commutator steadily increases with increasing t.

At least, that's what's expected of a system that approaches thermal equilibrium. There are at least two ways in which a quantum system might fail to fully explore its space of available states, even at effectively infinite temperature where energy barriers between states no longer matter. First, there's many-body localization, a cousin to the long-studied and simpler Anderson localization (see the article by Ad Lagendijk, Bart van Tiggelen, and Diederik Wiersma, PHYSICS TODAY, August 2009, page 24). In a many-body localized system, disorder in the Hamiltonian—for example, a spatially varying magnetic field acting on the particles in a spin chain—traps quantum information in localized regions and prevents distant spins from becoming entangled.

Second, there's prethermalization, in which a system's conserved (or quasi-conserved) quantities confine it to only a portion of its state space. In that case, the system quickly approaches a partially thermalized—or prethermal—steady state, which spans as much of the quantum state space as is possible subject to the conserved quantities. Full thermalization happens on a much longer time scale, if it happens at all.

Those exceptions to quantum thermalization can be used to construct extraordinary quantum systems, called time crystals, that enter perfectly periodic orbits in state space rather than chaotically exploring the whole space. (See the article by Norman Yao and Chetan Nayak, PHYSICS TODAY, September 2018, page 40.) Researchers want to understand more about how many-body localization and prethermalization work. What effects do they produce, and under what conditions? Does anything interesting happen at the boundary between thermalizing and nonthermalizing systems? Are nonthermalizing systems as rare in the quantum world as they are in the classical world, or are they common?

Into the unknown

Although OTO commutators have been considered theoretically for half a century, the first experimental steps toward using them to study quantum thermalization were taken only in 2017, when two groups independently measured OTO commutators for relatively simple systems. Xinhua Peng, of the University of Science and Technology of China, and her colleagues used NMR measurements on a molecular system containing four spins.[4] And Ana Maria Rey and colleagues at JILA looked at a lattice of trapped ions whose spins rotate collectively.[5] Both groups observed straightforward dynamics that agreed with simulations. Cappellaro and colleagues' fluorapatite experiments, on long chains of fluorine spins, are the first to study quantum thermalization in a system complicated enough that it's hard to simulate with high fidelity.

All three groups use similar techniques to turn back the clock on their quantum systems. With a repeating sequence of RF or microwave pulses, they apply a time-dependent perturbation to the system in order to modify the system's natural Hamiltonian. Carefully chosen pulse sequences can tune Hamiltonian parameters such as the spin–spin interaction strength, turn on or off an effective magnetic field, and even invert the sign of the whole Hamiltonian to make the system effectively propagate backward in time.

Because all the fluorine atoms in fluorapatite reside in identical chemical environments, they all resonate at the same frequency, so NMR can't address their spins individually. That means that Cappellaro and colleagues can neither prepare nor detect site-specific spin states, and they can't make different pairs of adjacent spins interact with different strengths. Rather, they're limited to looking at collective observables such as the total magnetization in some direction. Fortunately, an OTO commutator between two collective observables works just as well for quantifying the system's exploration of quantum state space as an OTO commutator between the states of distant spins.

An important parameter the researchers can tune is the strength of the interaction between the fluorine spins and the nearby phosphorus spins. The phosphorus spins are randomly oriented, so their net effect is a random, spatially varying magnetic field acting on the F-atom spin chain. The random field is just the kind of disorder to produce many-body localization, as Cappellaro and colleagues observed last year.[1] When they increased the strength of the disorder by applying an RF pulse sequence that enhanced the fluorine–phosphorus coupling, they saw that spin correlations progressively failed to spread along the fluorine chain.

In their latest work, they've turned to prethermalization.[2] They turn off the disorder in their effective Hamiltonian, and they replace it with a uniform effective magnetic field of strength g. When g is large enough relative to the fluorine–fluorine spin interaction strength J, the field makes the dominant contribution to the Hamiltonian, and the total energy is approximately proportional to the magnetization in the field direction. Because the magnetization is approximately conserved, the system can no longer efficiently explore the whole state space, which encompasses states with different total magnetization. The quasi-conserved quantity at high g should tip the system into the prethermal regime, as should be evident from OTO commutator measurements.

And the hallmark of the prethermal regime is just what they see, as shown in figure 2. The two panels depict the same data plotted in different ways. Each data point corresponds to a single measurement of an OTO commutator for a particular value of the effective field g and the time interval t. The low-field, rapidly thermalizing regime is exemplified by $g/J = 0.5$, shown by the vertical dashed line in figure 2a and the blue-green data in figure 2b; the OTO commutator swiftly grows with increasing t. On the other hand, in the high-field, prethermal regime, exemplified by $g/J = 1$, the OTO commutator grows for a short time and then stops, signaling that the system has reached a prethermal steady state.

Fluorapatite, therefore, has been shown to be a powerful model quantum many-body system that can be tuned into and out of the prethermalization and many-body localization regimes. Moreover, Cappellaro and colleagues have demonstrated that the OTO commutator can serve as an experimental probe of thermalization dynamics that may be applicable to other physical systems—including, perhaps, ones so complicated that theorists have no idea what to expect.

Johanna Miller

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An odd fluid shows its inner workings

Viscous forces drive waves along a two-dimensional fluid's free surface.

In a conventional fluid such as water, molecules tumble in random directions. Researchers in the fields of active matter, fluid dynamics, materials science, and condensed matter have long contemplated what would happen if the molecules' rotations were instead coordinated, creating a so-called chiral fluid.

Parity, or mirror, symmetry restricts the ways in which conventional fluids can respond to applied forces. A flow caused by an external force in a conventional fluid can break mirror symmetry and lead to phenomena such as instabilities and vortices. In nature, most fluids exist in a perturbed, symmetry-broken state. In contrast, a chiral fluid built of spinning particles breaks mirror symmetry without the need for an externally forced flow. Theorists posit that a chiral fluid could intrinsically possess new properties not found in conventional fluids.

Materials such as two-dimensional electron gases and liquid crystals break mirror symmetry. And collections of spinning magnets and rotating bacteria are examples of systems that exhibit some of the large-scale patterns, such as unidirectional edge currents, predicted for a chiral fluid.

Creating a liquid that behaves in similar ways has remained an elusive goal until now. Researchers in William Irvine's lab at the University of Chicago have for the first time developed a chiral fluid in the lab and identified the mechanisms that give rise to its unusual surface flows.[1]

One-way waves

The Irvine group's chiral fluid is a 2D colloidal suspension. To create the chiral

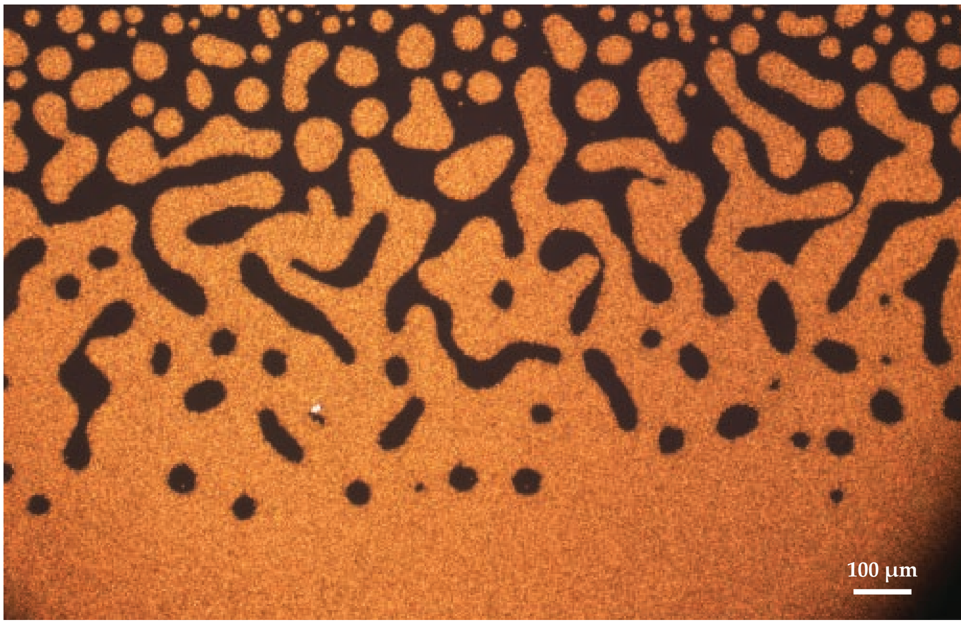

FIGURE 1. AN OPTICAL MICROGRAPH shows a bulk fluid of colloidal magnets (orange). After a few minutes of spinning, the particles attracted each other and formed a cohesive material. (Adapted from ref. 1.)

fluid, graduate students Vishal Soni and Ephraim Bililign and postdoc Sofia Magkiriadou, all at the University of Chicago, suspended billions of 1.6 μm hematite cubes, made by Soni and collaborator Stefano Sacanna (New York University), in a thin layer of water atop a glass slide. A rotating magnetic field caused the cubes to spin simultaneously in the same direction. After a few minutes of spinning, the colloidal magnets, shown in figure 1, attracted each other enough to behave as a liquid.

The material displayed several types of macroscale behavior reminiscent of a conventional fluid with positive surface tension. Nearby clusters of spinning particles merged into larger droplets. When the glass slide was tilted, the droplets bumped up against a hard edge and spread out, like raindrops on a windshield joining and then flattening when they hit the frame. When an obstacle was removed from the bulk, the voids quickly filled, like bubbles collapsing.

The material also displayed patterns not typical of a conventional fluid but expected for a chiral fluid. With no external stimulation beyond the rotating field, clockwise currents formed at the interface between the clockwise-spinning colloids and the suspending liquid. Such edge currents follow from the symmetry breaking caused by particles' active rotation in the chiral fluid.[2] Instantaneous velocity profiles of a chiral fluid droplet showed that the edge current extended to a finite depth δ into the bulk. For the 100-μm-diameter droplet shown in figure 2, the current depth was 4.5 μm.

High-resolution videos of the 2D

fluid's surface revealed a surprise: Unidirectional waves propagated along the fluid's free surface in the direction of the particle rotation. An overdamped system—such as a viscous fluid or a fluid inhibited by substrate friction—should not be able to sustain surface waves.

Pumping hematite

How does one account for the unusual phenomena? Navier–Stokes and other hydrodynamic equations provide a general description of a moving fluid based on conservation of mass, momentum, and energy. Transport coefficients known to be zero in a conventional fluid could, in theory, have a nonzero value in a chiral fluid. For example, nonzero rotational viscosity determines the rate at which local angular momentum differences equilibrate, and it should force a chiral fluid to rotate with the same angular velocity as the fluid's constituent particles. At the same time, friction between the fluid and the substrate should suppress the bulk fluid motion, and it affects the interior more than the edge. Higher friction results in a narrower edge current (smaller δ).

Irvine's group and his collaborators Michael Shelley (New York University) and Denis Bartolo (École Normale Supérieure de Lyon) sought to understand the experiments by using the most general model for chiral fluids and informing it with estimates of transport coefficients based on the individual particles' spinning rates on the glass substrate. When the researchers solved the hydrodynamic equations to determine the forces responsible for the observed surface wave patterns, they found a surprise. In a conventional fluid, viscosity acts as a damping force. But in the chiral fluid, viscosity and surface friction turned out to be what drove the propagation of surface waves.

"The best way to think of the wave propagation mechanism is to think of the wave in terms of mass flux," says Irvine. A chiral fluid always has an edge current, and a 2D droplet or a perturbed flat interface always has some nonzero curvature. The value of vorticity, the local spinning motion, is increased at regions of positive curvature (wave crests) and gives rise to enhanced mass flux relative to the average mass flux. Similarly, vorticity is decreased at regions of negative curvature (wave troughs) and gives rise to reduced mass flux. As shown in the sketch in figure 3, that differential mass flux effectively pumps fluid toward regions of zero curvature.

The transport resembles a shifting sand dune in which surface wind pushes material away from curved regions to-

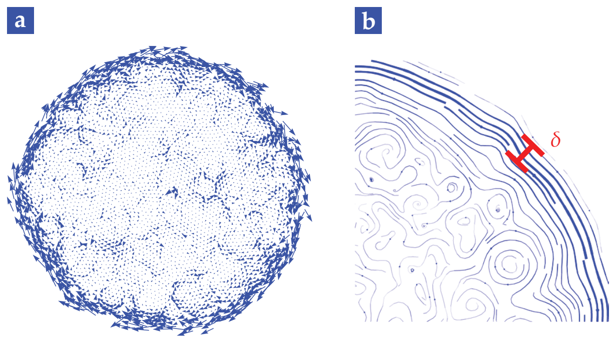

FIGURE 2. MEASURING THE VELOCITY OF EACH PARTICLE provides a flow profile **(a)** of a droplet of diameter 100 μm. **(b)** The flow is concentrated at the edge of the droplet in a layer of depth δ (4.5 μm). (Adapted from ref. 1.)

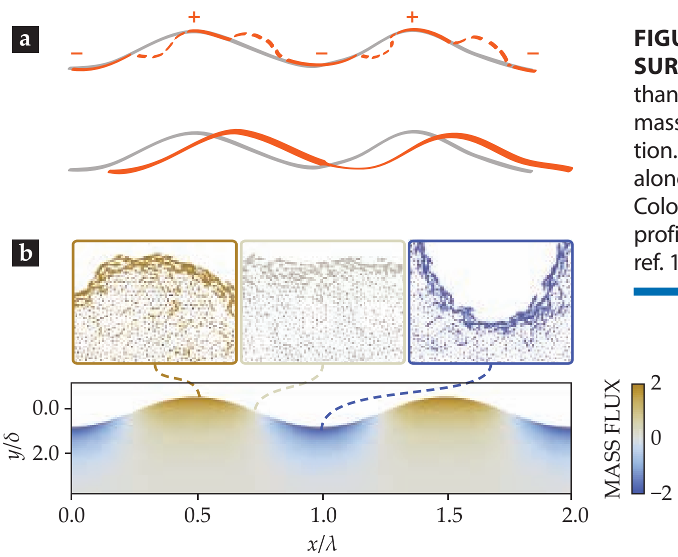

FIGURE 3. SURFACE WAVES PROPAGATE ON A CHIRAL FLUID'S FREE SURFACE. (a) In the presence of viscosity, fluid from regions with higher-than-average mass flux (+) gets pumped into regions with lower-than-average mass flux (–). The process propagates waves in the direction of particle rotation. **(b)** A sinusoidal perturbation (wavelength λ) generates a net mass flux along the fluid's free surface (height y, in an edge current of average depth δ). Color intensity indicates the relative strength of the flow. The inset velocity profiles show the microscopic origin of the mass flux variation. (Adapted from ref. 1.)

ward the flat wavefront; that motion leads to unidirectional wave motion. However, unlike the sand dune analogy, the surface motion is not an external force but a property intrinsic to the chiral fluid. The researchers dubbed the mechanism "edge-pumping."

That's odd

Surface waves in most fluids lose energy to their surroundings through viscous damping, which diminishes the waves' motion and flattens the fluid's surface. For the colloidal chiral fluid on the glass substrate, however, the observed damping rate resulted from the competition between surface tension and substrate friction. Surface tension flattens any curves, and substrate friction restricts any movement of the material.

To find out how damping arises when substrate friction is reduced, Soni, Bililign, and Magkiriadou placed droplets of the colloid suspension on an air–water interface. The lower-friction situations also sustained surface waves. However, those waves did not flatten according to the equations that described their glass-substrate counterparts—the measured damping rates could no longer be explained by surface tension alone.

The researchers found their answer in a phenomenon called odd or Hall viscosity, a term coined in 1998 by Joseph Avron.[3] Odd viscosity can be understood by decomposing the edge-current velocity into its tangential and perpendicular components.[4] Whereas shear viscosity is a stress that acts on a fluid in the same direction as the flow, odd viscosity is a stress that acts on a fluid orthogonally to the direction of the flow. In the case of a chiral fluid, the odd viscosity gives rise to a flow perpendicular to an applied pressure and thus, perhaps counterintuitively, does not dissipate energy.

In Irvine's lab, the odd viscosity flattened the chiral fluid's surface waves in a manner similar to surface tension. For the glass substrate, damping could be fully accounted for with a zero value of odd viscosity. For the air–water interface, the magnitude of the odd viscosity was of the same order as the shear viscosity. Although researchers at Leiden University had demonstrated in 1966 that odd viscosity could exist in a magnetized gas[5] and researchers at the University of Manchester recently reported odd viscosity in a 2D electron gas,[6] Irvine and colleagues have now provided the first measurement of it in a chiral fluid.

Thomas Powers, a physicist at Brown University, says, "The field of active matter is still a little theory and computation heavy, and there aren't that many clean experimental systems. This is a nice one with relatively new features." The chiral fluid provides the first platform for probing and designing materials with properties that arise from uniformly spinning particles. The model system could also help predict behaviors that may emerge in some plasmas or in charge carriers in 2D electronic materials.

Rachel Berkowitz

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Superconductivity is found in a nickel oxide

A long-sought structural and electronic analogue of the cuprate superconductors has finally been synthesized.

In 1986 Georg Bednorz and Alex Müller discovered superconductivity in an oxide of lanthanum, barium, and copper—$La_{1.85}Ba_{0.15}CuO_4$. The achievement won the researchers a Nobel Prize the following year (see PHYSICS TODAY, December 1987, page 17) and triggered an explosion of research in condensed-matter physics. Although that oxide superconducts below a relatively low 30 K, the transition temperatures T_c of subsequent cuprates exceed those of any previously known superconductor by almost an order of magnitude. Yet despite 33 years of research since then, no consensus has emerged as to what causes their superconductivity.

Prospects appear brighter now that a new family of cuprate-like superconductors has been realized. Harold Hwang, his postdoc Danfeng Li, and their colleagues at SLAC and Stanford University have successfully synthesized neodymium strontium nickel oxide, $Nd_{0.8}Sr_{0.2}NiO_2$, which superconducts below 15 K.[1]

Hwang's group did not stumble on the superconducting nickelates purely by serendipity. Rather, their quest was inspired by a theoretical prediction that was in turn informed by what experimenters and theorists have learned about cuprates

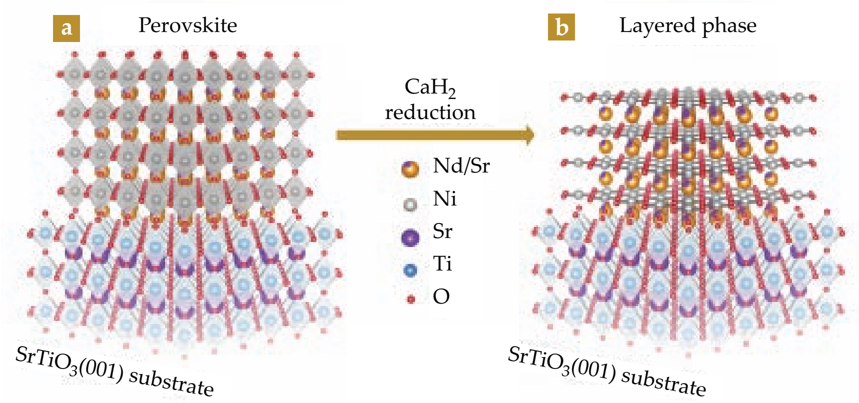

FIGURE 1. CHEMICAL TRANSFORMATION from a three-dimensional perovskite to a 2D layered phase. **(a)** The formation of superconducting $Nd_{0.8}Sr_{0.2}NiO_2$ starts with an epitaxially grown crystal of $Nd_{0.8}Sr_{0.2}NiO_3$ on a strontium titanate ($SrTiO_3$) substrate. **(b)** That phase is then reduced using calcium hydride, which strips off one-third of the oxygens to leave NiO_2 planes separated by a network of neodymium and strontium atoms. (Adapted from ref. 1.)

over the years. Despite their different chemistry, near the Fermi level Ni and Cu have an apparently similar electronic structure, which is dominated by a single $d_{x^2-y^2}$ orbital. The differences of detail between the families should shed light on the origins of superconductivity.

Mott insulators

At room temperature the cuprates are such poor conductors that they barely qualify as metals. Their stacks of closely spaced CuO_2 planes are separated by charge reservoirs. Each unit cell in the CuO_2 plane has an odd number of electrons, and their states are so well localized that it takes a large amount of energy for an electron to hop from one lattice site to another. Indeed, the cuprates are materials whose single-particle band structure tells you should be metals but are, in fact, Mott insulators because of electron–electron repulsion that creates a traffic jam.[2]

The magnetic moments of the material's nearly filled Cu^{2+} $3d^9$ shell arrange themselves in a two-dimensional checkerboard with strong antiferromagnetic interactions between neighboring spin-½ Cu ions, each separated by an O ion. The usual approach to studying the cuprates' peculiar superconductivity is to modify the charge-carrier concentration in the CuO_2 planes through chemical doping. (For instance, one could introduce holes by substituting Ba^{2+} for La^{3+}.) Hole doping suppresses the antiferromagnetic order, and superconductivity sets in at a critical doping concentration.

Soon after the cuprates were discovered, Princeton University's Philip Anderson argued that their superconductivity is somehow inherited from the properties of a doped Mott insulator. One strategy for gaining further insight was to look for superconductivity in solids that incorporate similar structural, magnetic, and electronic features—a 2D lattice, spin-½ ions, and *d*- and *p*-orbital hybridization among them. Replacing Cu with another transition metal was an obvious path.[3] Nickel sits next to Cu in the periodic table, and theorists Vladimir Anisimov, Danil Bukhvalov, and Maurice Rice predicted in 1999 that if Ni could be synthesized in the unusual +1 oxidation state in a lanthanum nickelate lattice, it would have the same electronic configuration as Cu^{2+} in the cuprates.[4] Each would have a single hole in its 3*d* shell.

By partially substituting strontium for neodymium in $NdNiO_2$, Hwang's group finally found a superconducting analogue. Although the transition temperature of 15 K is meager by cuprate standards, the achievement has generated enormous enthusiasm. Just four weeks after the researchers' publication,[1] more than a dozen theory papers had appeared on arXiv.org.

Long time coming

Several groups have made $LaNiO_2$ compounds as powders and thin films. The first synthesis was done in the early 1980s, before Bednorz and Müller's award-winning cuprate work. Nickelates ordinarily prefer an octahedral coordination—a network of Ni atoms surrounded by four oxygens in one plane and two "apical" oxygens above and below it. In

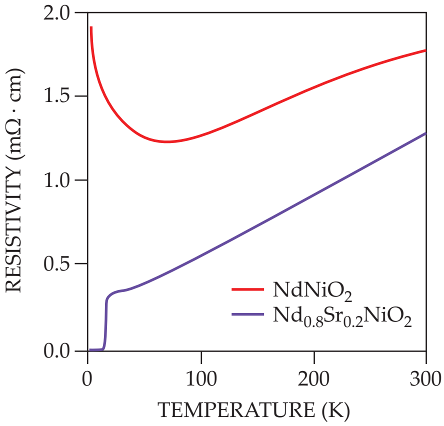

FIGURE 2. UNDOPED NEODYMIUM NICKELATE (red) exhibits metallic temperature dependence at high temperature, with a resistive upturn below 70 K. By contrast, strontium-doped nickelate (blue) behaves like a metal down to a superconducting transition that begins at 15 K and drops to zero resistance at 9 K. (Adapted from ref. 1.)

1983 chemists Michel Crespin, Pierre Levitz, and Lucien Gatineau realized they could start with that phase—a 3D perovskite $LaNiO_3$—and expose it to hydrogen gas to reduce it into $LaNiO_2$ with a 2D planar geometry.[5]

In the perovskite phase, planes of LaO alternate with those of NiO_2. Reducing the perovskite strips out about a third of the oxygens (the apicals) while leaving the NiO_2 framework, whose planes are then separated only by La atoms. The layered structure ($LaNiO_2$) that remains has both the square-planar geometry and a transition-metal oxidation state present in the cuprates.

The 1983 synthesis and most others that followed produced polycrystalline powders. The large surface-to-volume ratios and random orientations of the crystals complicated the reduction chemistry: Reactions sometimes introduced Ni-metal inclusions and other defects or led to decomposition. A major step forward was to replace H_2 gas with a metal-hydride reducing agent, which turned out to be safer and more reliable.[6] But it wasn't until 2009 that Kyoto University's Masanori Kawai and coworkers epitaxially grew the reduced planar structure as a single-crystal thin film.[7] With the film grown on a strontium titanite ($SrTiO_3$) substrate, the reactions became more tractable.

Hwang, Li, and their colleagues used the Kyoto group's recipe as a springboard. They improved it in key ways: First, they swapped out La for Nd to make the material more conductive. Nd ions are smaller than La ions, and they shrink the nickelate's in-plane lattice constant. The Stanford group also chemically doped the starting perovskite material with holes by substituting 20% of the Nd^{3+} ions with Sr^{2+}. Earlier groups had doped the nickelate or reduced it, but not both. (An unpublished account of a doped, reduced sample was reported in Oxford University chemist Mike Hayward's 1999 thesis, but no superconductivity was reported.)

The sequence also mattered. Only after the group had grown the Sr-doped $NdNiO_3$ lattice at the high temperature—600 °C—needed for it to crystallize atop $SrTiO_3$ did they reduce it. That step took place at a much lower temperature, 280 °C, and produced the layered phase shown in figure 1. The resulting samples measure 2.5 × 5 mm^2.

In search of a mechanism

Resistivity measurements of the doped nickelate revealed a superconducting transition, shown in figure 2. But establishing superconductivity is just the start. Although the nickelate's lattice matches that of the $SrTiO_3$ substrate, the reduction process compresses the material. As Hwang points out, he and his colleagues faced the unusual situation in which the substrate that stabilizes the growth of the nickelate also strains it. Straining a superconductor's lattice, either by applying pressure or substituting atoms of a different size, often changes T_c.

The Stanford team has yet to fully optimize the growth parameters and doping levels. X-ray diffraction revealed that if the precursor compound is reduced for too long a time or at too high a temperature, the film decomposes and diffraction peaks disappear. "The superconducting phase appears stable," says Hwang, "but only if not pushed beyond the sought-after Ni^{1+} oxidation state."

Studying the differences between cuprate and nickelate superconductors could provide needed clues to the mechanism of unconventional superconductivity. According to the Bardeen-Cooper-Schrieffer theory of the late 1950s, lattice phonons mediate the Cooper pairing of electrons in conventional noncuprate superconductors such as aluminum or lead. But that interaction is thought to be too weak for Cooper pairs to survive much above 30 K at ambient pressures. And whereas conventional superconductors have isotropic, *s*-wave symmetry, the superconducting wavefunction in the cuprates has *d*-wave symmetry—that is, it changes sign upon rotation by 90°. Many theorists now believe that the emergence of Cooper pairs in the vicinity of magnetism and other forms of electronic order is central to the cuprates' unconventional superconductivity.[2]

Once one starts doping a cuprate, the charge carriers delocalize because of hybridization between Cu 3*d* and O 2*p* orbitals. But what prompts the material at some critical doping to superconduct remains unknown. A magnetic origin for the pairing mechanism could arise from so-called superexchange, in which spin fluctuations in the antiferromagnetic interactions between neighboring Cu sites are mediated by O atoms that separate the Cu atoms.

In the cuprates, the energy of the Cu $d_{x^2-y^2}$ orbital is nearly degenerate with that of the O 2*p* orbitals, which makes the hybridization—and thus the spin fluctuations—particularly strong. By contrast, the energy levels of Ni and O orbitals are much different, which weakens the spin fluctuations. Indeed, according to neutron-diffraction studies, no sign of magnetic order appears in $NdNiO_2$ down to 1.7 K.

What should researchers make of the fact that superconductivity has now been found in a compound whose spin fluctuations may be so far less pronounced than in the cuprates? Answering that question will likely require answering others. For example, what happens at various levels of hole doping and on various substrates? And what is the role of rare-earth 5*d* electrons? Some theories advocate that they screen the Ni 3*d* spins—perhaps explaining why magnetism is suppressed.

Mark Wilson

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Trade wars and other geopolitical tensions strain US–China scientific collaborations

Researchers are increasingly on edge about collaborations that until recently were encouraged.

This summer a tenured physics professor at a Texas university received a letter from his employer expressing concern about the professor's plans to cochair a conference in China. The letter noted that he had not submitted paperwork to request foreign travel, the conference was at a university listed as restricted by the US Department of Commerce, and his fellow cochair was a member of China's "Thousand Talents" foreign recruitment program. The letter cited financial and reputational risks to the university. The physicist—a US citizen who is not of Chinese descent—cochaired the conference anyway; so far, at least, he has not suffered any negative consequences.

Franklin Tao, a chemistry professor at the University of Kansas, was indicted on federal charges in July for allegedly holding a paid position in China that he hadn't disclosed to his US employer or to the US agencies that funded his research. He faces up to 20 years in federal prison and fines of up to $500 000.

A Chinese physicist who has worked in the US for many years recently waited in limbo for months for a visa to reenter the US. Fearing repercussions, he and the Texas physicist each requested that their identities and universities be concealed; several scientists in both the US and China declined to speak with Physics Today for this story.

Such incidents—and many others like them—have cast a chill over scientific collaborations between researchers in the US and China. "There is a bipartisan feeling in Congress that the Chinese are engaging in unscrupulous practices," says physics Nobel laureate David Gross of the University of California, Santa Barbara; he is president of the American Physical Society (APS) and is a foreign member of the Chinese Academy of Sciences. "The effect is to discourage scientific collaboration and mobility completely."

Denis Simon has studied Chinese science and technology for decades and is executive vice chancellor of Duke Kunshan University, located near Shanghai. "If you are a scientist in the US, irrespective of ethnicity, and you are involved with Chinese counterparts, this is a very difficult time," he says. "I think it's reached its worst point in 40 years."

The Beijing–Washington relationship is "seen now through a national security lens, with deep distrust," says Robert Daly, director of the Wilson Center's Kissinger Institute on China and the United States. "We are in a comprehensive competition for influence across every sphere—trade, military, financial, and the development and marketization of technologies." Science and technology are key to many aspects of dominance—5G, artificial intelligence, synthetic biology, quantum computing. That's why universities are caught in the middle, he says. "How does the US preserve national security and maintain openness without being a complete sucker?"

Security versus openness

In a 16 September letter to the US research community, Kelvin Droegemeier, who heads the White House Office of Science and Technology Policy, wrote, "As researchers, we must acknowledge the changing geopolitical and international scientific landscape: United States policies and practices must evolve thoughtfully and appropriately to meet current and future challenges." He did not explicitly name China.

Singling out recruitment programs sponsored by foreign governments, Droegemeier said that some have features that are "unacceptable and inconsistent with our research values and research principles." He listed the failure to disclose foreign funding, affiliations, and appointments; diversion of intellectual property (IP) or other legal rights; breaches of contract and confidentiality; unapproved foreign labs; and "surreptitious gaming of the peer-review process."

His missive followed statements along the same lines by the National Institutes of Health in August 2018 and by the Department of Energy in January and NSF in July of this year. DOE and NSF have restricted participation in foreign recruitment programs.

No one doubts that there have been incidents of people secretly pulling in two salaries ("double dipping"), committing industrial espionage, hacking computers, stealing IP, and engaging in other

CHINA INSTITUTE IN AMERICA

XIAOXING XI OF TEMPLE UNIVERSITY speaking in June at an event about the current climate for Chinese American researchers. The Temple University condensed-matter physicist was arrested in May 2015 for allegedly sending technological secrets to China. The charges were dropped.

misdeeds. But the scale of the problem is unknown, says Gross. "If you have two bad eggs in the middle of hundreds or thousands, who cares? We [at APS] are trying to inform the agencies of the enormous harm to the US research enterprise if we are no longer attractive to foreign scientists. It won't be just the Chinese. I am very disturbed by living in a country where the actions of my own government make me afraid of collaborating with scientists from abroad."

At the moment murky guidelines lead many US institutions and individual scientists to play it safe. "Regardless of citizenship, people don't want to get into trouble," says Xiaoxing Xi, "so they reduce their interactions with China." A condensed-matter physicist at Temple University, Xi was arrested at his home in May 2015 and charged with sending restricted technology information to China. The charges were dropped four months later, when it turned out that government prosecutors had misinterpreted their own evidence. But by then his career had suffered—he had not been allowed on campus or permitted to talk to his students, and his university had transferred his grants to other principal investigators. His research group has withered from 15 to 3. Now, he says, "with more Chinese scientists being charged and scrutinized, it makes me feel very unsafe."

Tobin Smith, vice president for policy at the Association of American Universities, points out that the biggest concerns are often ethical, not legal. "We have to find the line that protects us and allows us to maintain openness," he says. "It starts with the federal agencies being clear about the rules, and the rules should be harmonized across the agencies."

China with perks

The US is a global leader in higher education and research. That preeminence is widely recognized as being due largely to the country's ability to attract top students and scholars from around the world. In a 4 September letter to US agency heads, some 60 professional societies wrote that "scientific progress and U.S. economic development have been vastly accelerated by bringing international minds together and [have] helped to drive innovation and discoveries" in cancer and genetics, gravitational waves, green chemistry, food safety, and other areas. APS and the American Institute of Physics (AIP), which publishes PHYSICS TODAY, were among the signatories.

Formal collaborations and student exchanges with China ramped up after a 1979 agreement between the two countries. And for the past few decades, students from China have been among the largest international cohorts in the US. In recent years, non-US citizens have made up roughly half of individuals earning physics PhDs from US institutions, and more than a quarter of them are from China, according to Patrick Mulvey of AIP's Statistical Research Center. Across all fields more than 360 000 students from China were in the US for the 2017–18 academic year, according to the Institute of International Education.

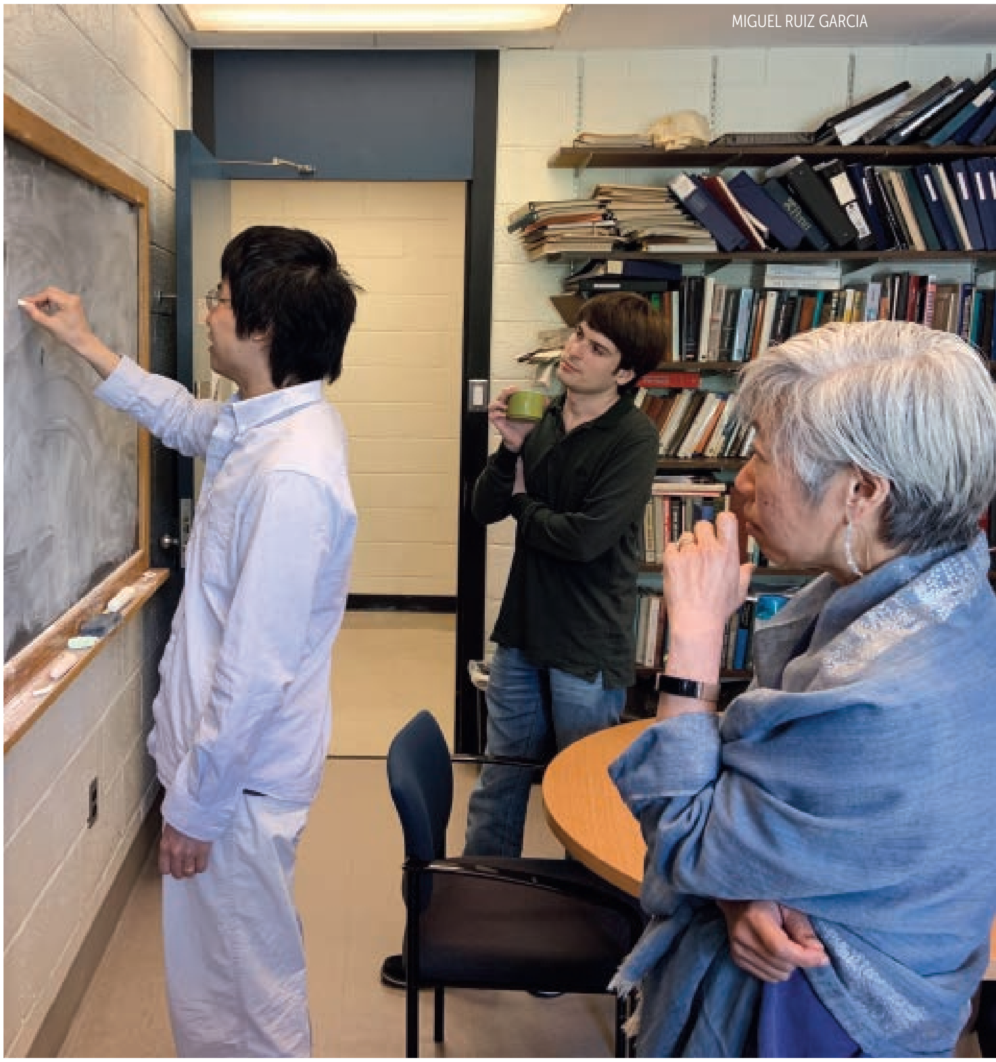
But Chinese students and scholars are finding it increasingly difficult to obtain visas for the US. For example, at least 20 Chinese scientists missed this year's APS March meeting because of visa delays. And visas for Chinese citizens now often require annual renewal instead of being valid for 5 or 10 years, as previously; students in robotics, aviation, and high-tech manufacturing are among those affected. Students from China and some other countries may hesitate to go to the US—and US faculty members may hesitate to take them on—given the uncertainty about staying in the country to complete their programs of study.

"I have a postdoc from China, and he hasn't been home for eight years," says Andrea Liu, a theoretical physicist at the University of Pennsylvania. "We have collaborations with people in France, but he can't go there because he might not get back into the US. It's hurting his career."

Liu sometimes collaborates with a former postdoc who went back to China nearly a decade ago. "He's terrific, and he has amazing computational resources that far exceed what we have here," she says. Robert Ritchie, a materials scientist at the University of California, Berkeley, and at Lawrence Berkeley National Laboratory, agrees that nowadays "China has far more resources in terms of money and equipment than we do in the US. Some of the things I want to do, I can't do here." But in the past year or so, he says, "everything is coming under increased scrutiny. One feels a bit inhibited now in dealing with Chinese groups."

The top Chinese students used to stay in the US after completing their studies, says Ritchie, whose collaborations with scientists in China go back at least 15 years. "That's not true anymore. The situation in China has improved for them, they are attracted back with perks, and they wonder if they can thrive here."

Haiyan Gao, a nuclear physicist at Duke University, notes that Chinese scientists do not lack opportunities to work with researchers in other countries. "If you are counting on their collaboration, and in the end they can't get a visa, the US loses out. We have seen more Chinese


MIGUEL RUIZ GARCIA

ANDREA LIU (right), a physics professor at the University of Pennsylvania, with postdoc Ge Zhang of China and graduate student Sean Ridout of Canada. Zhang hasn't gone home to see his family or traveled to conferences outside the US in several years because of the uncertainties surrounding visas.

colleagues devote more effort to Europe." China has built up its domestic know-how, she says. "To cut things off now is frustrating."

Tightened rules, heightened fears

Reports of increasing threats and pressure from US government agencies have prompted universities, national laboratories, and funding agencies to tighten their practices and more rigorously enforce existing rules. For international business travel, for example, US government employees and subcontractors are required to obtain a country clearance cable from the State Department that includes information intended to be helpful for their trip. In earlier days, says a DOE-funded scientist who requested anonymity, "no one cared, but now they really pay attention, and there have been times when I didn't get my cable until I landed in China." He adds that in a "preemptive move" to avoid having to ask approval from DOE, his institution rejected his request to attend a conference and give talks in China next year.

Many funding agencies and universities now discourage US researchers from accepting hospitality from their Chinese hosts. Betty Tsang, a physicist at the National Superconducting Cyclotron Laboratory at Michigan State University, says that in the past, "when I would go for collaborative work or conferences to China, I would pay to get there out of my grants, and the Chinese hosts would pay for my expenses while I was there." By following her lab administration's recent advice to reject such support, she and her students can't afford to go as often, she says. "I'm keeping my existing collaborations, but I'm not initiating new ones." The hassles and uncertainties about what will be allowed are too great, she explains.

Written requirements for hiring Chinese nationals at Los Alamos National Laboratory (LANL) have not changed, notes Alan Hurd, who oversees collaborations between the lab and universities. But after DOE released its January memo, he says, "hiring managers are frequently avoiding Chinese candidates." Even before that, DOE employees felt the crackdown especially keenly. One DOE-funded scientist who was asked by Chinese colleagues to apply for the Thousand Talents program says his institution initially approved his application but later told him to decline the offer. DOE has traditionally valued international collaborations, the researcher says, but currently "they would rather you stay local. At least I can still exchange emails [with Chinese colleagues] without logging them."

An anonymous Chinese physicist says he has stopped splitting his professional life between the US and China. The same goes for his colleagues, he adds, who are either returning to China or remaining in the US. The arrests, firings, visa delays, and tone from the funding agencies make people nervous. "The gray area is unsafe," he says.

Adding to the anxiety is that the crackdowns are uneven across subfields and campuses. In fusion research, for example, DOE this year renewed a grant for joint work between scientists in the US and China. Houyang Guo, who is based at the DIII-D tokamak, a national user facility in San Diego, California, and coordinates US–China fusion activities for DOE, says he has experienced no problems. Even so, when he traveled to China in May, he took a company loaner laptop for the first time instead of his own, and when he returned he was debriefed both by US Customs and by General Atomics, the company contractor that runs DIII-D for DOE. Both events were firsts for him.

Fu-Chun Zhang, director of the Kavli Institute for Theoretical Sciences in Beijing, says new US restrictions haven't affected his institute, although he did hire a postdoc earlier this year whose offer to go to LANL was rescinded. And Zhang noted lower-than-usual participation by US colleagues at a workshop in China in September 2019 on strongly correlated electronic systems. At least one physicist was denied approval from DOE to attend the workshop, he says. "It will take time to see the real effects of the US clampdown. It's not positive. Scientific exchange is important for both the US and China."

Liu says she is "extremely concerned about what is going on." As an APS board member, she attended an unclassified briefing in February by the FBI and the Office of the Director of National Intelligence requested by APS. The briefing covered the potential risks of academic espionage, intellectual property theft, and other dangers posed by foreign actors, with a focus on China. "My main concern is that the FBI get it right before they

DIII-D NATIONAL USER FACILITY

SCIENTISTS AT THE DIII-D TOKAMAK headquarters in San Diego, California, remotely conduct plasma physics tests on the Experimental Advanced Superconducting Tokamak, in Hefei, China. The collaboration has not experienced problems due to US–China tensions, and the Department of Energy recently renewed its funding.

indict someone," she says. "With Wen Ho Lee they didn't understand the science," she says of the LANL scientist who was arrested and charged with espionage in 1999 (see PHYSICS TODAY, July 2006, page 23). "They got the science wrong with Xiaoxing Xi of Temple University." It ruins a person's life, Liu says, and it's bad for science. "It fosters a climate of distrust and racial profiling. As an ethnic Chinese—I've never even been to China—it makes me uneasy."

Full disclosure

Disclosure is crucial, says Rebecca Keiser, who heads NSF's Office of International Science and Engineering. Double dipping and foreign talent recruitment programs can be a problem because funding agencies need to know that the scientists named on a proposal have the time to do the work they are proposing, she explains. "We have seen an increase of nondisclosure of other support and appointments that pose conflict and overlap." And some of the foreign contracts contain clauses that conflict with values of research integrity and openness. For example, she says, US researchers have been asked to sign that they won't tell their home institution they are taking a second position, or that they will provide their Chinese partners with prepublication information, data, and ideas. "NSF funds basic research," she adds, "and we want it open, but when it's ready."

A few years ago Tsang was offered a position in China that would have let her spend three months there each year. A well-equipped lab and extra manpower would have come with the position, she says. But the fine print said that the Chinese institution would own the copyrights to works, inventions, patents, and other intellectual property she produced during the contract period. "There was no consideration of the contributions from my primary institution, where I would be doing most of the work," she says. She turned down the offer.

The change in attitude toward China "has been brewing for a while," says the AAU's Smith. He attributes the increased wariness to China's economic rise and its increasingly authoritarian government. And he points to testimony in February 2018 by FBI director Christopher Wray as an "inflection point." Wray said that China is using university personnel as "nontraditional collectors of information to take back to China, and universities are naïve to the problem."

Duke Kunshan University's Simon says that China has moved from the margins to the mainstream to become a maker as well as a taker of scientific knowledge. The chill in the US research community comes, he says, from several sources: the FBI and intelligence agencies visiting universities, the universities in turn warning their faculty, the funding agencies cracking down, and the overarching trade war. The chill creates a cloud over collaborations, he says. "The irony is that when asymmetry dominated, the cooperation proceeded well, and China was the greater beneficiary. But now the US has more to gain, and the US is concerned China may be eating our lunch."

With a nod to the Cold War, Simon notes that the trust built between scientific communities has withstood tense times and helped to provide continuity despite difficult political relations. But this time, "scientific knowledge is the essence of the political problems."

Deep dissatisfaction

A growing number of academic leaders are speaking out for academic freedom. In a 30 August column in the *Washington Post*, "No, I won't start spying on my foreign-born students," Columbia University president Lee Bollinger writes that "stewards of major research universities couldn't contain intellectual freedom even if we wanted to." He acknowledges that the "unauthorized use of intellectual property by overseas competitors is a serious problem," but says, "surveillance of foreign-born scholars in this country is the wrong solution."

In May the Office of Science and Technology Policy formed a committee comprising representatives from science agencies and from security agencies to develop uniform approaches to balancing commercial and national security against open research environments. NSF has requested that JASON, an independent scientific advisory group, conduct an analysis of the risks of espionage and IP theft; the group's report is expected by the end of the year. And the National Academy of Sciences has begun holding expert roundtables to assess risks and examine possible policy responses.

Still, no balance between security and openness will please everyone, says the Wilson Center's Daly. Meanwhile, global problems like pandemics and climate change demand global cooperation. "The problem is truly new, and it's full of paradoxes. How much vigilance can openness endure? How much openness can security tolerate? Any tradeoff will be deeply unsatisfactory."

Toni Feder

Separating signal from noise to solve a nuclear puzzle

Pacific Northwest National Laboratory develops radioisotope and particle detectors that can distinguish the production of medical isotopes from the testing of nuclear warheads.

PNNL

BOB RUNKLE (left), manager of signatures science and technology at Pacific Northwest National Laboratory, and the author suit up for a tour of PNNL's shallow underground lab, where ultrapure copper parts are made for detection instruments.

Ensuring compliance with the moratorium on nuclear testing, observed by all nations but North Korea, is the responsibility of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). But its global international monitoring system (IMS) is sometimes confounded by the production of the medical isotope precursor molybdenum-99, which has a nearly identical radioactive signature to nuclear explosions. The problem is worsening as demand for technetium-99m, the most widely used medical radioisotope and the offspring of ^{99}Mo, continues to grow.

The surest radioactive indicator that a nuclear test has recently taken place is the presence of radioisotopes of xenon in the atmosphere, says Ted Bowyer, a nonproliferation program manager at Pacific Northwest National Laboratory (PNNL). As a noble gas, xenon doesn't interact with the environment and is more difficult to contain underground than other particulate fission products.

Home to the largest nuclear nonproliferation program in the Department of Energy's national lab complex, PNNL in the 1990s developed the technology for xenon detection and analysis software used by CTBTO's IMS. The lab and its industrial partner Teledyne Brown Engineering are developing a next-generation xenon monitor that Bowyer expects will replace many of the current IMS machines. Known as beta–gamma coincidence spectrometers, the instruments work by detecting the nearly simultaneous emission of a beta particle and a gamma ray that is the hallmark of radioxenon decays. A plastic scintillator detects the beta particles; a well holding sodium iodide is excited by gamma rays. The new detectors will be twice as sensitive as the previous generation and capable of analyzing more samples per day, he says.

Eighty IMS radioisotope-monitoring stations are spread around the globe (see the article by Matthias Auer and Mark Prior, PHYSICS TODAY, September 2014, page 39). Each is equipped with germanium-based gamma-ray spectrometers capable of identifying many of the several dozen fission products that are indicative of a nuclear test. But radioxenon is the only gas; the others are particulates. Radioxenon isotopes from a nuclear test are present at levels of around 1 part in 10^{23} in the atmosphere, compared with stable xenon, which occurs at 87 parts per billion, says Bowyer.

Half the IMS stations are equipped

with xenon monitors. Several of them found unmistakable evidence for two of North Korea's six nuclear tests that occurred between 2006 and 2017. Recognizing the other tests required careful analysis of weather data and sophisticated models developed at PNNL to sift out background interference.

Radioxenon is also emitted during other fission processes, and the world's half-dozen ^{99}Mo production reactors are the largest source. Their outsized contribution to the xenon background occurs when ^{99}Mo targets, which contain uranium, are removed from reactors for immediate chemical processing. The sudden release of four xenon radioisotopes can be confused with a nuclear explosion. By contrast, radioxenon created in commercial reactors mostly remains locked inside spent fuel elements, and any reprocessing of spent fuel occurs well after xenon radioisotopes have decayed away.

Demand for ^{99}Mo is forecast to increase by 1.5% a year, so its interference with nuclear detection will continue to worsen, Bowyer says. In the US alone, at least three companies may be starting

PNNL

PACIFIC NORTHWEST NATIONAL LABORATORY researchers Rey Suarez (left) and Jim Hayes developed the next-generation radioxenon detection system, called Xenon International, for uncovering evidence of clandestine nuclear explosions.

new fission-based ^{99}Mo production in the coming years. (Other US startups use nonfission processes; see "Competitors abound to produce key medical isotope," PHYSICS TODAY online, 21 February 2019.)

To better pin down the interfering emissions, the US government is offering to install source monitors at all ^{99}Mo production sites. To date, reactors in Belgium and Australia have taken up the offer.

The lab is one of 16 facilities around the world that confirm analyses of IMS test samples, which are shipped in bottles. A system being tested at PNNL happened to be on at the time of the 2011 Fukushima nuclear disaster and was the first to find the radioxenon. From the plume's content—100 000 times the radioxenon background—scientists were able to determine within several days that the fuel elements in the damaged reactors had ruptured. The Fukushima accident proved useful in helping PNNL to calibrate xenon dispersion models, says Bowyer. The IMS monitoring sites "all lit up like crazy" throughout the Northern Hemisphere and, a few weeks later, in the southern half of the globe, he says.

The lab wasn't involved in identifying the radioactive plume from an August 2019 accident at a Russian military site. Russia switched off the country's four IMS stations following the accident, which was believed to have occurred during the development of a nuclear-powered cruise missile, to prevent the incident from being recorded, US officials alleged.

A happy connection

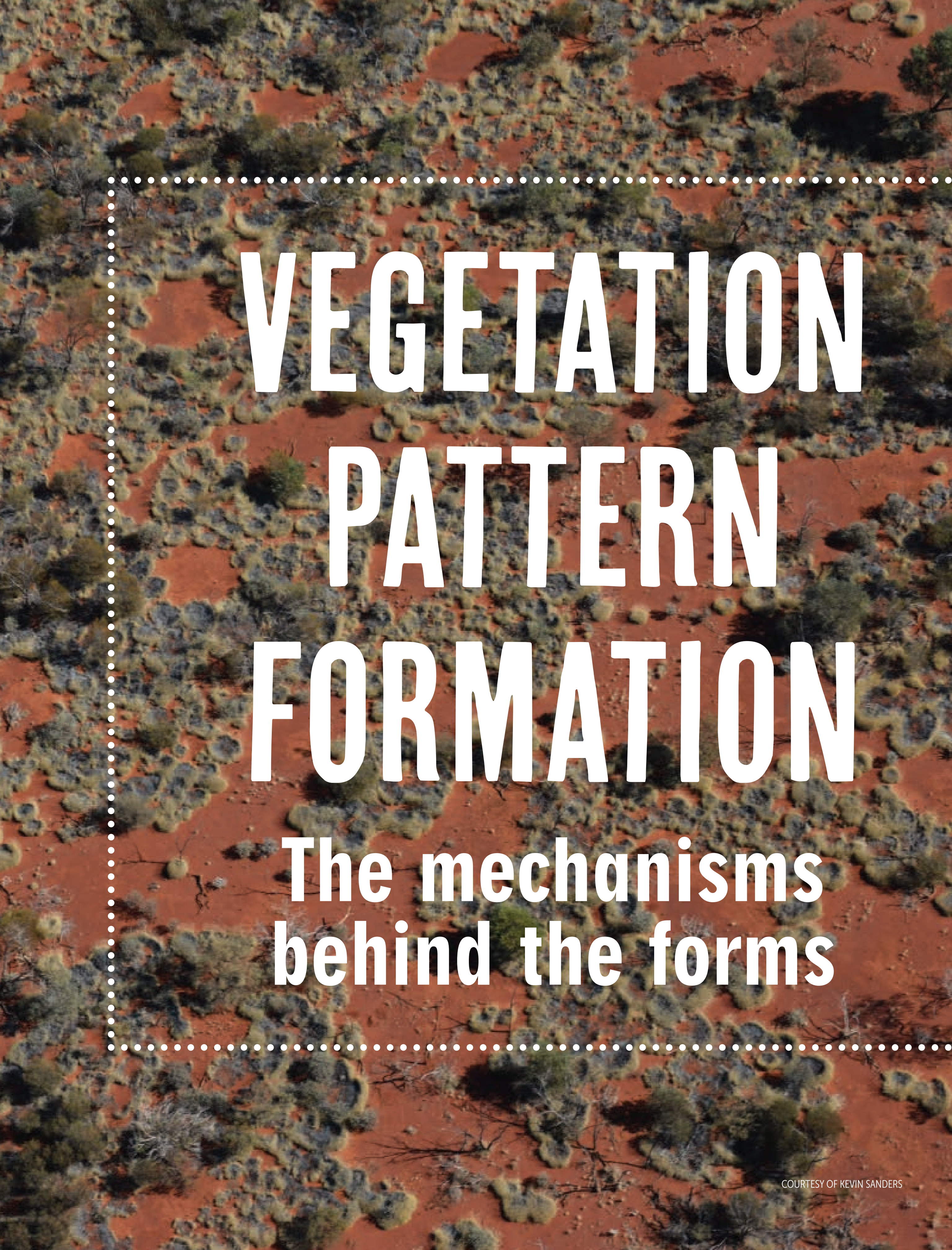
Some of PNNL's detection expertise comes by virtue of its being adjacent to the Hanford Site, the main source of Cold War plutonium production, in southeastern Washington. "The science of nuclear fuel is our heritage," says Jim Fast, a physicist and lab fellow. Other capabilities resulted from what Bowyer describes as "a happy connection between basic science and national security applications." Roughly one-fifth of PNNL's annual budget and programs are supported by DOE's basic research arm, the Office of Science, which oversees the lab.

Fast, who spends about half his time on national security programs, initiated a small high-energy physics program at PNNL when he arrived in 2005. He had previously worked at Fermilab helping develop the shielding and cryogenic components for the Majorana Neutrinoless Double-beta Decay Demonstrator at the Sanford Underground Research Facility in South Dakota (see PHYSICS TODAY, February 2013, page 19). PNNL is currently supporting the Belle II experiment at Japan's KEK accelerator, which is studying the properties of B mesons (see PHYSICS TODAY, April 2015, page 18); the SuperCDMS experiment at Canada's SNOLAB (see PHYSICS TODAY, September 2014, page 25); and the Axion Dark Matter Experiment project at the University of Washington (see the article by Karl van Bibber, Konrad Lehnert, and Aaron Chou, PHYSICS TODAY, June 2019, page 48).

Ensuring that the insides of detection instruments are kept free of naturally occurring radioisotopes such as potassium-40 and carbon-14 is critical for scientific research and treaty monitoring alike. To that end, PNNL electroforms ultrapure copper components used for instrument shielding and vacuum cryostats in a laboratory clean room located 12 meters underground.

The underground lab also houses one of two instruments in the world that can measure argon-39 at levels found in the environment, Fast says. Its half-life of 270 years and very low abundance make ^{39}Ar difficult to measure, adds Fast. Researchers at the US Geological Survey use the instrument for radioargon dating of aquifer recharge rates. Argon that's been underground in water for hundreds of years will contain less radioactive ^{39}Ar than will the atmosphere. New groundwater will have slightly more of the radioisotope, which indicates a faster aquifer recharge cycle.

David Kramer PT



VEGETATION PATTERN FORMATION

The mechanisms behind the forms

COURTESY OF KEVIN SANDERS

Ehud Meron is a professor of physics and the Phyllis and Kurt Kilstock Chair in Environmental Physics of Arid Zones in the Jacob Blaustein Institutes for Desert Research at Ben-Gurion University of the Negev in Israel.

Ehud Meron

A simple principle relating growth to lateral water transport explains the variety of self-organized vegetation patchiness.

Mathematician Alan Turing deciphered the German Enigma code during World War II and laid the foundations of computer science as a new discipline. But toward the end of his short life, he made a lesser-known yet groundbreaking contribution. Interested in the development of patterns and shapes in biological systems, in 1952 Turing published a paper entitled "The chemical basis of morphogenesis."[1] In the theoretical study, he showed that a homogeneous system of chemical substances that react with each other and diffuse in space can self-organize into spatially periodic distributions. His work received limited attention until four decades later, when the behavior was experimentally observed.[2,3] The confirmation of Turing's prediction led to a surge in the number of studies of so-called Turing patterns, first in chemical and biological contexts and more recently in ecological contexts.[4]

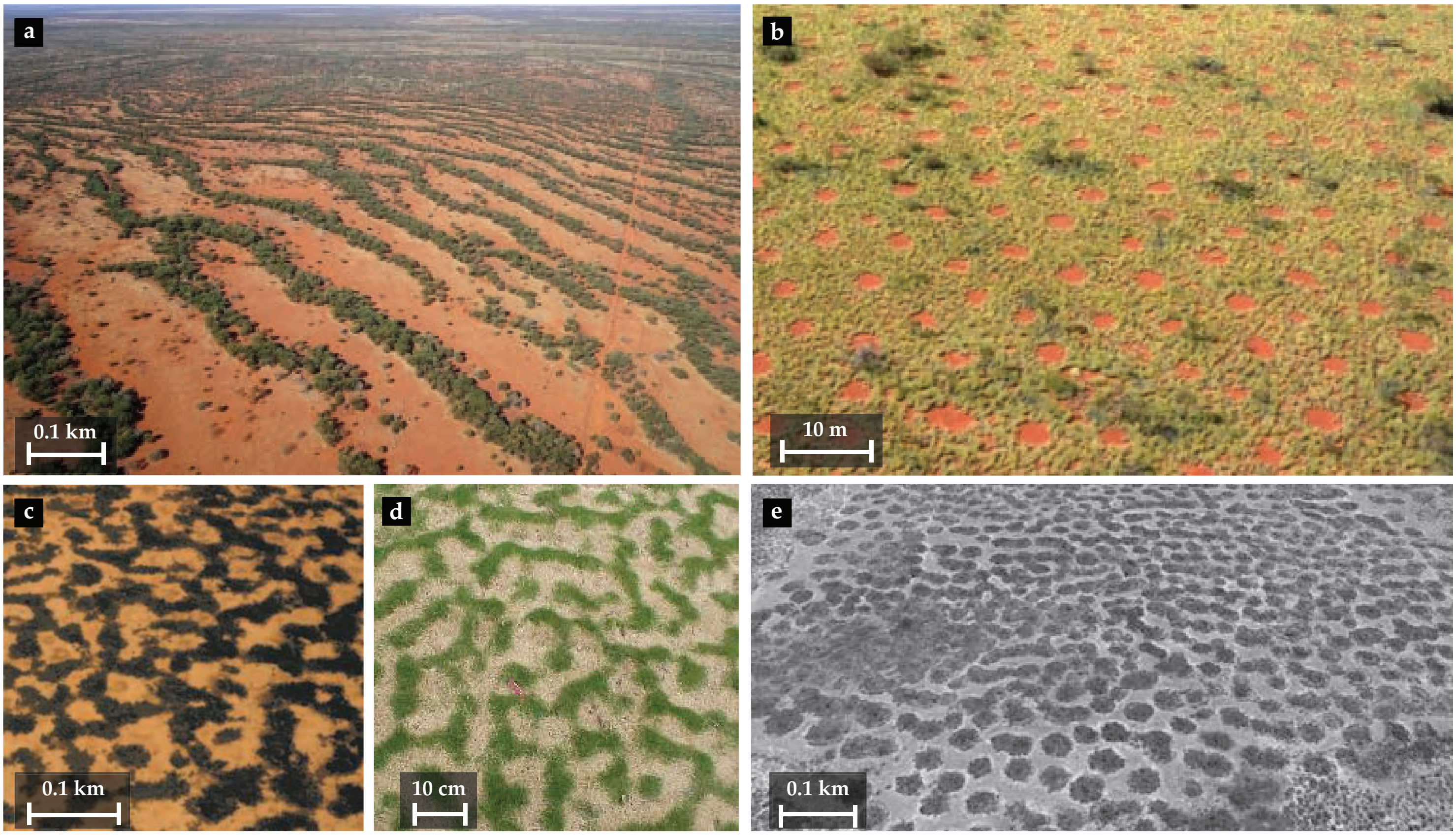


FIGURE 1. DRYLAND VEGETATION can form a range of patterns. **(a)** Banded woody vegetation on a sloped terrain in Australia (photo courtesy of Stephan Getzin). **(b)** A gap pattern of herbaceous vegetation in Australia (from ref. 11). **(c)** A labyrinthine pattern of woody vegetation in Niger (from ref. 4). **(d)** A labyrinthine grass pattern in Israel (from ref. 10). **(e)** A spot pattern of woody vegetation in Zambia (from ref. 18).

In a time when aerial photographs, let alone satellite images, of remote regions were hardly available, Turing could not have imagined the possible realizations of his predictions for dryland vegetation. Those who have traveled through arid and semiarid regions may have noticed the patchy character of the landscape, which is made up of vegetation patches surrounded by bare-soil areas or vice versa. Usually the patchiness appears irregular, which has traditionally been attributed to variable microtopography and soil heterogeneities. It came as a big surprise when aerial photographs of dryland regions, first in East Africa[5] (even before Turing's paper) and later in many regions across the world, revealed strikingly regular vegetation patterns with various morphologies that were not recognizable from the ground.

The first morphology to receive extensive scientific attention was parallel vegetation bands on gently sloped terrains,[6–8] a recent example of which was observed in northwestern Australia (see figure 1a). In flat terrains, additional morphologies have been reported, including nearly hexagonal vegetation gap patterns (figure 1b), labyrinthine stripe patterns (figures 1c and 1d), and nearly hexagonal spot patterns (figure 1e). As figures 1c and 1d show, the same type of pattern can appear with different plant species and on characteristic length scales that vary by orders of magnitude.

Vegetation patterns are not limited to drylands.[4] Recently they have also been observed in underwater seagrass maps obtained using hydroacoustic techniques.[9] The growing recognition of vegetation pattern formation as a fundamental phenomenon observed worldwide with different plant species has led to the emergence of a vigorous new research field at the interface between spatial ecology, nonlinear physics, and applied mathematics,[10] where Turing's ideas are essential.

Positive water–biomass feedback

The spontaneous appearance of large-scale spatial order is often a result of a local positive feedback loop that amplifies small perturbations throughout the whole system and thereby induces an instability of the original state. But what positive feedback loop could drive the formation of the observed periodic vegetation patterns? Assuming that pattern formation in water-limited ecosystems can be explained solely in terms of vegetation growth and water availability, researchers have proposed a feedback loop, illustrated in figure 2, in which water transport toward locations of growing vegetation accelerates vegetation growth that, in turn, enhances the water transport.[4,10,11]

An instability driving uniform vegetation to become patterned can then be understood as follows: Consider a landscape of almost uniform vegetation and an area with slightly denser vegetation than its surroundings. That area draws slightly more water than its surroundings and becomes even denser. The amplified deviation from the originally uniform vegetation closes the feedback loop and sets the ground for a

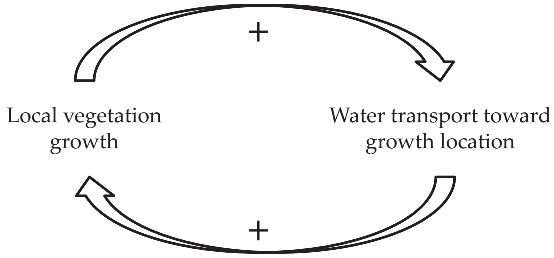


FIGURE 2. A POSITIVE FEEDBACK LOOP drives vegetation pattern formation in water-limited systems. Feedback mechanisms accelerate vegetation growth in denser patches and inhibit growth in adjacent sparser patches, and thereby promote vegetation pattern formation. (Adapted from ref. 10.)

new amplification loop. While the transport of water toward denser vegetation accelerates the growth there, it inhibits the growth in the surrounding areas from which water is being taken. The instability that results generates nonuniform vegetation growth and the formation of a pattern.[4]

The first part of the feedback loop (the lower arrow in figure 2) is fairly obvious in ecosystems where the limiting growth factor is water availability. But why should vegetation growth enhance water transport (the upper arrow)? The answer depends on the particular transport mechanism.

One possible process is overland water flow, shown in figure 3a. Bare-soil areas in drylands are often covered by physical or biogenic crusts that reduce the infiltration rate of surface water into the soil. As a consequence, the infiltration rates in sparsely vegetated areas are lower than those in densely vegetated areas. Further contributing to that infiltration contrast are the plants' roots, which increase the soil porosity and thus the infiltration rate around the plants. The higher rate that develops as the vegetation grows denser in a given location enhances overland water flow toward that location, and that can account for the portion of the feedback loop indicated by the upper arrow in figure 2.

Another mechanism is conduction by laterally extended plant roots (see figure 3b). The biomass of a plant consists of an aboveground part, or shoot, and a belowground part, or root. Those two entities are not independent—larger shoot means larger root; their relationship is expressed in terms of the root-to-shoot ratio. As the shoot grows, the lateral extension of the root zone enhances water transport because it allows for water uptake and conduction from a larger volume.

The root-to-shoot relationship also is essential in enhancing water transport for laterally confined roots (see figure 3c). In that transport mechanism, water diffuses through the soil toward locations of accelerated vegetation growth. Stronger water uptake by deeper roots depletes the water content relative to the surrounding soil and creates soil-water gradients, which induce diffusion.

The three mechanisms are each associated with a positive feedback loop that can induce a pattern-forming instability on its own. In general, the feedback loops can act in concert, and their relative importance changes with environmental conditions. The interplay between them has interesting implications for community structures because of the different water distributions associated with each transport mechanism and the niches those distributions provide for other species.[10,11] The feedback loop associated with overland water flow acts to increase the soil-water content in a vegetation patch, whereas those loops associated with water diffusion and conduction by lateral roots act to decrease that content by their strong water uptake. In landscapes consisting of shrubs and annual plants, dominance of the overland water flow feedback loop can facilitate annuals growing near or under the canopies of shrubs; dominance instead of feedback loops involving strong water uptake can result in the exclusion of annuals from the vicinities of shrubs.[11,12]

Upscaling information from local to global

The biomass–water feedback loops describe local plant-scale processes. But does that small-scale information translate to large-scale collective behaviors? Specifically, can the capabilities of the biomass–water feedback loops induce pattern-forming instabilities in uniform vegetation?

One indispensable tool for addressing such questions is a heuristic mathematical model, built so as to capture the feedback loops associated with overland water flow, water conduction by laterally extended roots, and water transport by diffusion.

Two types of modeling approaches are primarily used to study plant population dynamics: discrete agent-based models, also called individual-based models, and those based on continuum partial differential equations (PDEs). Agent-based models are stochastic computational algorithms that go down to the level of individual plants and often describe each plant in great detail. PDE models, on the other hand, do not address individual plants; rather, they describe deterministic processes at small spatial scales. A plant population is then represented by a continuous biomass areal density.

The PDE approach is more heuristic but has the advantage of lending itself to the powerful methods of pattern-formation theory.[10] But is it a suitable approach to describe small populations of discrete entities, for which demographic noise and extinction are usually a concern? The answer is definitely positive. Unlike animals, plants are immobile organisms that cannot migrate away from environmental stresses. Instead, they generally cope by changing their phenotype. That plasticity is reflected in, among other things, the ability of a single plant to change its viable biomass by orders of magnitude; such flexibility justifies embodying vegetation biomass as a continuous variable. Another consideration that supports the continuum modeling approach is the near irrelevance of extinction events; even in cases of complete plant mortality, long-lived seeds have nonvanishing probabilities of germinating whenever the biotic and abiotic conditions allow and can revive the population.

In 2004 Erez Gilad and colleagues introduced a PDE model that captures all three feedback loops.[12] It contains a biomass variable $b(x,t)$ that quantifies the aboveground areal density of the plant population, and additional biomass variables in the case of a plant community consisting of several populations. There are also two water variables: One describes the soil's water content, $w(x,t)$; the other, the overland water height, $h(x,t)$. Because of the nonlocal nature of water uptake, the model includes integrals over a localized root-kernel function, $g(x,x')$, that captures the lateral root distribution of a plant. Thus the term that describes biomass growth in the biomass equation contains the integral $\int g(x,x')w(x')dx'$, which accounts for plant

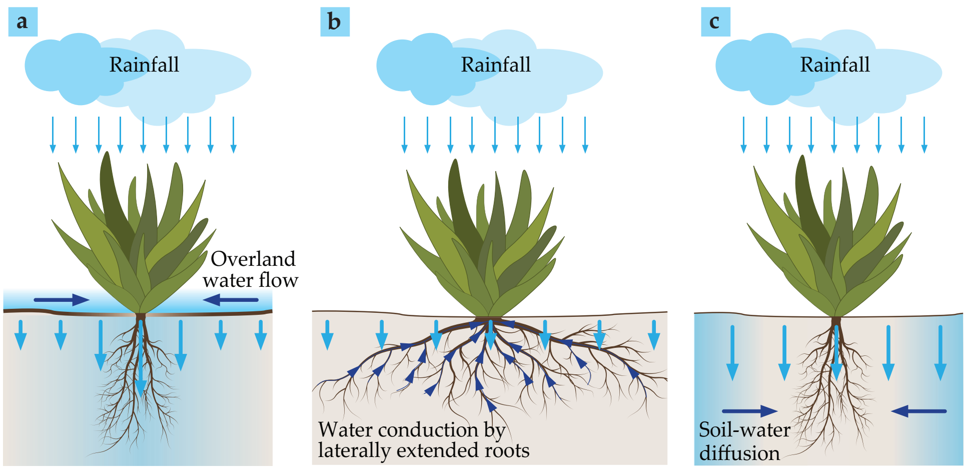


FIGURE 3. THREE FORMS OF WATER TRANSPORT promote flow toward vegetation patches. **(a)** Overland water flow is induced by differences in water infiltration, which is low in bare-soil areas covered by soil crusts, indicated here by a thick ground-surface line, and high in vegetated areas. **(b)** Laterally extended root systems allow plants to increase their water uptake by drawing from a larger volume. **(c)** Water diffuses from water-rich soil in nonvegetated areas with high infiltration rates to water-poor soil in vegetated areas. Dark-blue arrows denote water transport toward growing vegetation. Short light-blue arrows denote low surface-water infiltration rates, and long light-blue arrows denote high infiltration rates. Shaded blue in the soil denotes high water content.

growth at x due to water availability w at all other locations x' in the root zone of x. Likewise, the soil-water equation contains the integral $\int g(x',x)b(x')dx'$, which captures water uptake at x by all plants whose roots extend to that point.

The positive feedback loop associated with laterally extended roots is captured by making the width of the localized root kernel g increase monotonically with the aboveground biomass b, which accounts for the root-to-shoot relation.[12] Water infiltration variability is included in the model by making the infiltration rate of overland water into the soil biomass-dependent; the infiltration rate is higher in more densely vegetated areas.[4]

Applications of the general model to specific ecological contexts often allow simplifications. For example, a model for species with confined root zones can be simplified by using delta-function root kernels; that assumption results in the replacement of the nonlocal integral terms by local algebraic functions. A model for ecosystems with sandy soil characterized by high infiltration rates can be simplified by eliminating the overland-water equation.[10]

PDE models of dryland ecosystems often oversimplify the complex ecological reality and leave aside many factors, such as the effect of transpiration on the atmosphere, soil erosion and deposition, and various plant-physiology processes. They should be viewed as tools that can provide deep insights into given ecological contexts rather than make quantitative forecasts. The models also constitute an indispensable source of well-grounded hypotheses for empirical studies. Such studies are typically long running because of the time scales on which vegetation grows; the hypotheses being tested should therefore be carefully chosen.

Emergence of large-scale periodicity

Analytical and numerical studies of the model discussed above have shown that all three biomass–water feedback loops can induce a nonuniform stationary instability of uniform vegetation when the precipitation rate p drops below a critical value p_T. Such an instability is characterized by the monotonic growth of a spatially periodic mode and the formation of a periodic or nearly periodic stationary pattern.[11] The characteristic wavenumber k_c of the growing mode depends on intrinsic ecosystem properties such as the root-to-shoot ratio and the infiltration contrast.

A convenient way to graphically describe the model solutions and show their existence and stability ranges is to draw a bifurcation diagram such as the one in figure 4a. The horizontal axis represents a control parameter—here the precipitation rate p—and the vertical axis represents a suitable measure of a chosen state variable, such as the biomass spatial average $\langle b\rangle$ or its L^2 norm $\|b\| \propto \int|b|^2dx$. A common convention in such diagrams is to represent stable solutions with solid lines and unstable solutions with dashed lines.

Figure 4a shows a bifurcation diagram of stationary solutions in one spatial dimension. The simplest solutions, shown in orange, are constant; they represent bare soil ($b = 0$) and uniform vegetation. The bare-soil solution is stable for low precipitation, at which seeds do not germinate, but it becomes unstable at some threshold p_U. Above that threshold a spatially uniform mode begins to grow and drives the system toward a uniform vegetation state. But that state is stable only at sufficiently high precipitation values $p > p_T$. If the precipitation decreases below that threshold, uniform vegetation becomes unstable. Unlike the uniform mode that grows beyond the bare-soil instability, the mode that grows below p_T is spatially periodic (figure 4b). That drives the system toward a stable periodic pattern (the green line in figure 4a).When $p_U < p_T$, as is the case in figure 4a, the destabilization of the bare-soil state above p_U results in a convergence to the periodic-pattern state because the uniform vegetation state is unstable.

In addition to the periodic solution that emerges from the uniform vegetation solution branch at $p = p_T$, the bifurcation diagram shows another periodic solution, indicated by the blue line, that emerges from uniform vegetation at a slightly lower precipitation threshold. Figure 4c shows an example of that periodic solution, which is characterized by a lower wavenumber. That solution extends to the highest precipitation rate, p_H, at which periodic solutions exist. Many additional periodic solutions that are not shown in the figure also appear with decreasing wavenumber as the precipitation decreases further. The last solution is a single hump (figure 4d), indicated by the purple line, which describes a single vegetation spot. That solution extends to the lowest precipitation value p_L at which viable vegetation still exists. Empirical indications of periodic patterns with different wavenumbers have recently been reported.[13]

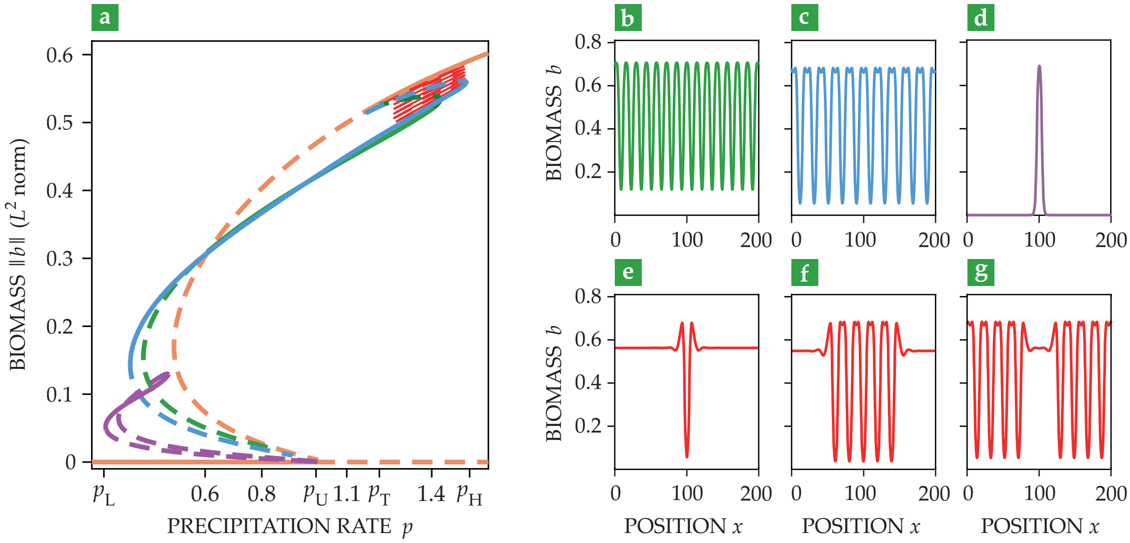


FIGURE 4. PERIODIC AND LOCALIZED PATTERNS emerge from a nonuniform instability of uniform vegetation. **(a)** A bifurcation diagram of one-dimensional solutions of a two-variable model that shows the dependence of the L^2 norm of the biomass b on the precipitation rate p.[11] Solid lines represent stable solutions and dashed lines represent unstable solutions. The orange lines denote two constant solution branches: bare soil with $\|b\| = 0$, which is unstable for $p > p_U$, and uniform vegetation, which is unstable for $p < p_T$. The green line represents the periodic solution that bifurcates from the uniform-vegetation solution at p_T. The blue line represents the periodic solution that extends to the highest precipitation value p_H. The purple line denotes a single-hump solution with zero wavenumber and defines the lowest precipitation value, p_L, at which spatial patterns exist. The branches of the snaking red line represent localized solutions of different sizes. **(b–g)** Spatial dependencies of solutions that correspond through their colors to the various branches in panel a. Numerical values refer to dimensionless quantities. The corresponding dimensional quantities are $P = p \cdot$ (160 mm/yr), $B = b \cdot$ (1 kg/m²), and $X = x \cdot (1 / 10\sqrt{2}$ m). (Courtesy of Yuval R. Zelnik.)

The green and blue periodic-solution branches that emerge from the uniform vegetation solution appear in subcritical bifurcations—that is, a precipitation range exists where both uniform vegetation and periodic patterns are stable states. That range extends from the threshold p_T, at which the uniform vegetation state loses stability, to a threshold beyond which periodic solutions cease to exist (see figure 4a).

Within that range there exist a multiplicity of stable localized patterns of increasing size, beginning with a gap in otherwise uniform vegetation (figure 4e), through gap-pattern domains of increasing sizes (figure 4f), to a periodic gap pattern with a single missing gap (figure 4g). In figure 4a, those localized patterns are denoted by the red curve that snakes back and forth between the uniform and the periodic solution branches; that behavior has been termed homoclinic snaking.[14] The localized patterns act as building blocks for many irregular but stable patterns that are hybrids of uniform vegetation and periodic gap patterns. Empirical indications of such hybrid patterns have been reported in studies of grassland gap patterns in Namibia.[15]

In two-dimensional isotropic systems, nonuniform stationary instabilities generally result in the emergence of periodic hexagonal patterns. Such patterns are formed by the simultaneous growth of three resonant modes with wavevectors of the same magnitude k_c but oriented 120° relative to each other.[10] Indeed, simulations starting from a nearly uniform vegetation state slightly below p_T result in a nearly hexagonal gap pattern, as figure 5 shows. Such dynamical behavior has been used to explain observed hexagonal gap patterns in Australian grasslands, shown in figure 1b, and how they differ from apparently similar hexagonal gap patterns in Namibian grasslands.[16]

Ecosystems with sloped terrains are not isotropic, and the patterns that emerge from simulations are mostly stripes oriented perpendicular to the slope. That finding is consistent with empirical observations,[8] such as the stripes in figure 1a. In fact, in sloped terrains, the instability of uniform vegetation involves the oscillatory growth of a spatially periodic mode,[10] which results in vegetation bands migrating uphill.[17] That migration, which has been empirically confirmed,[8] can be understood as a result of the better growth conditions for plants at the top of a vegetation band, where runoff accumulates, than at the bottom part, where runoff is lost.

A basic principle for vegetation patterning

The emergence of periodic patterns from uniform vegetation as the rate of precipitation decreases can be viewed as a population-level mechanism—one that involves many individual plants—to cope with the water stress caused by reduced rainfall. Partial plant mortality and the concomitant formation of bare-soil gaps create an additional water source for the surrounding vegetation through the various forms of water transport illustrated in figure 3. The water contributed by bare-soil areas to surrounding vegetation compensates for the reduction in direct rainfall and allows for the survival of the remaining vegetation patches. The utility of that principle shows up in the system's response to further reductions in rainfall: Less rain should result in larger bare-soil areas capable of contributing more water to adjacent vegetation patches. That area increase is indeed observed in simulations, and it can be realized in different ways.

The simplest mechanism by which bare-soil areas can increase is by a contraction of vegetation patches. In one-dimensional patterns, such as banded vegetation on sloped terrains, that

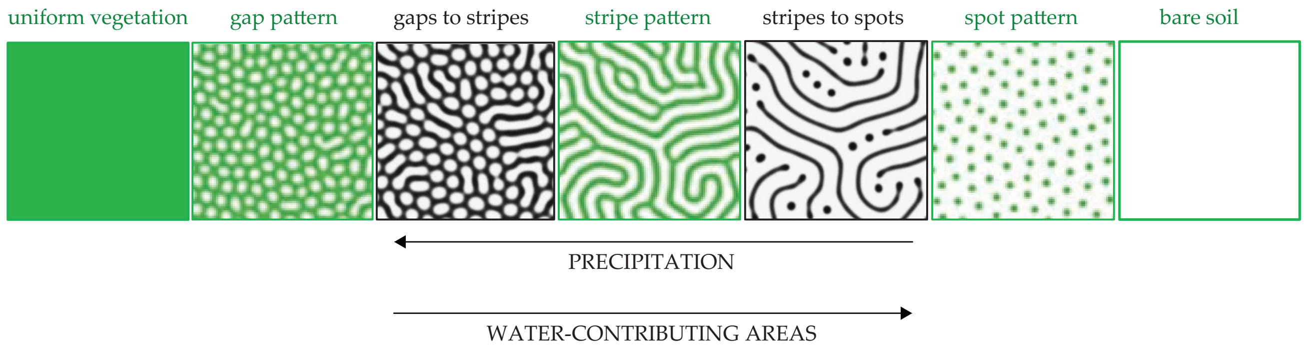


FIGURE 5. THE FIVE BASIC VEGETATION PATTERNS along the rainfall gradient (green panels) and snapshots of two morphological transitions (black-and-white panels) as obtained by model simulations with slowly decreasing rates of precipitation. As precipitation decreases from left to right, bare-soil areas, which contribute water to adjacent vegetation areas, should increase in size for the vegetation to remain viable. That increase results in two morphological transitions: Gaps become stripes through the merging of bare-soil gaps, and as vegetation disintegrates further, those stripes turn into spots.

contraction amounts to vegetation bands narrowing while their number stays constant, which keeps the pattern's wavenumber unchanged. That response mechanism occurs along the branch of any periodic solution, such as the green and blue lines in figure 4a. Those solution branches extend to precipitation values lower than that of the uniform-vegetation solution (upper orange line), which manifests the positive effect of vegetation patterning and band thinning on the vegetation's capacity to survive water stress. Another way in which bare-soil area can increase in response to decreasing precipitation is through a reduction in the number of vegetation patches. That response is reflected in transitions to periodic solutions with lower wavenumbers as p decreases.

Two-dimensional patterns have yet another mechanism for increasing bare-soil area in response to decreasing rainfall: the morphological transitions illustrated by the black-and-white panels in figure 5. The first transition involves the merging of adjacent bare-soil gaps in a hexagonal pattern to form bare-soil stripes. The resulting pattern persists to lower precipitation values until a second morphological transition takes place in which stripes break into spots. Those two transitions, together with the instability of uniform vegetation to hexagonal gap patterns and the collapse of spots to bare soil, form a sequence of five basic vegetation states along the rainfall gradient, shown by the green panels in figure 5.

From patterns to function

The discussion so far has focused on understanding mechanisms of vegetation pattern formation and accounting for the variety of patterns observed in drylands. But beyond the obvious curiosity raised by those fascinating phenomena, there are important open questions related to functional aspects of vegetation patterning that call for further study. The functioning of dryland ecosystems is currently threatened by two main factors. The first is global climate change and the likely more frequent extremes, such as severe droughts, that accompany it; the second is human intervention, which often involves extracting resources, such as livestock feeding, and imposes additional stresses on already vulnerable ecosystems.

Climate extremes can cause abrupt and irreversible transitions in vegetation that lead to alternative dysfunctional stable states, such as bare soil. How do the many stable vegetation pattern states affect such transitions? Can they mitigate the effects of extreme droughts by providing alternative vegetation response pathways that culminate in functional patterned states rather than collapse to bare soil?

Human intervention also often results in detrimental outcomes. But whereas researchers need to understand the many stable ecosystem states to address the effects of climate extremes, they have to study unstable ecosystem states to deal with human intervention. Directions in which an ecosystem departs from its unstable states can act as road signs for judicious human interventions. Following those signs may circumvent detrimental outcomes by directing ecosystems toward functional states. However, identifying the relevant unstable states for particular human interventions remains a challenge.

Understanding the transient dynamics of dryland ecosystems caused by climate extremes and human intervention calls for interdisciplinary collaborations between physicists, applied mathematicians, and ecologists. By working together, they can assimilate the concepts and methodologies of pattern formation into ecological theories and facilitate research progress.

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The new science of NOVAE

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The discovery of γ-ray emission from novae has been used not only to better understand sudden brightening events but also to answer some old questions and raise new ones.

On 8 November 2016, Kwan-Lok Li of Michigan State University discovered a new bright source of γ rays in the constellation Sagittarius using the Large Area Telescope (LAT) aboard the *Fermi Gamma-Ray Space Telescope*. Li and his colleagues had been inspecting the LAT data from that part of the sky for any γ rays from a nova, in which the light from a previously obscure star suddenly becomes much brighter. No γ-ray source had been seen at the location until two weeks after the start of the optical eruption (see figure 1). Although such events were first discovered in 2010, the 2016 eruption is the most dramatic example of the sudden appearance of γ rays in optical novae.

A nova eruption occurs in binary star systems containing a white dwarf star, the dense nuclear ash of a low-mass star supported by the quantum mechanical repulsive force among electrons (see box 1). Eruptions, like the one shown in the opening photo, are usually found because of their spectacular and sudden optical brightening, which occurs over a matter of days. Some nearby ones—about a quarter of the way to the Milky Way's center or closer—are bright enough to see with the naked eye. The novae in nearby galaxies are also bright enough to be observable. But of the estimated 50 or so nova eruptions per year in the Milky Way,[1] only about 10 are actually discovered because of interference from the Sun, crowding of stars in the galactic center region, and dust obscuration.

After peak intensity, the nova typically takes weeks or months to dim by a factor of 10. Spectroscopic observations show that matter is ejected from novae at velocities ranging from about 300 km/s to almost 10 000 km/s. Novae with high-velocity ejecta fade more quickly, a property that was best studied in a sample of novae observed in the Andromeda galaxy.[2]

The companion star supplies the white dwarf with fresh, hydrogen-rich fuel for the nova eruption. With enough fuel, the material on the surface of the white dwarf achieves a critically high temperature and pressure, and a thermonuclear runaway (TNR) ensues, which lasts for about 1000 seconds and generates more than 10^{45} ergs of energy. In many cases, the TNR is strong enough to violently eject much of the matter the white dwarf accumulated from its companion (see box 2). And much like in volcanic eruptions, the ejecta provide most of the light show.

Nova eruptions leave the underlying binary systems largely unchanged. The companion star is most often a red dwarf, which is smaller than the Sun. Some 10–30% of all novae come from a white dwarf paired with a red giant. But most such binaries have never been seen to have nova eruptions. Evidence of a nova eruption becomes difficult to find a few decades or centuries after it explodes. All that can be seen is that the white dwarf is accreting fresh new fuel, so eventually a new nova eruption will occur. The white dwarf usually takes from a decade to a few hundred thousand years to accumulate enough material to trigger a TNR, though in one spectacular case in the Andromeda galaxy, the accumulation takes just one year.[3]

Nova ejecta are multiphased. Recent multiwavelength observations make it apparent that hot plasma and cold dust coexist with the warm (10 000 K) phase of ejecta. In particular, the surprise discovery of the strong γ-ray emission from novae has led to renewed interest in the hot phase of the ejecta. With multiwavelength observations pushing theoretical developments, the mystery of the strong γ rays from novae is being unraveled.

The warm phase

At optical peak, the emission from a nova is dominated by visible light, emitted by warm ejecta, that readily absorbs incoming photons. The visible-light photons interact with material deep inside the ejecta mostly by electron scattering. The process creates a surface of last scattering. As the ejecta expand and thin out, the surface recedes, and instruments can see farther into the ejecta. As the size of the surface shrinks, its effective temperature increases. The luminosity of a nova remains roughly constant because nuclear fusion continues at the white dwarf surface at a quasi-steady rate. As the peak of the spectral energy distribution moves from visible light to the UV, the photospheric emission from the white dwarf can escape without interacting much with the ejecta. At that stage, the photosphere has a temperature between 500 000 K and 1 million K, and much of its emission is in the extreme UV, which is easily absorbed by the interstellar medium. Although the UV emission becomes more difficult to observe, the photosphere does emit detectable, low-energy x rays. The *Neil Gehrels Swift Observatory* can respond rapidly to unforeseen celestial events and has provided a wealth of details regarding the visible, UV, and soft x-ray behavior of novae.[4]

Radio and IR wavelengths provide even more information about novae. By assuming a reasonable density distribution in the ejecta, one can infer its total mass from a single radio spectrum. With multiple radio spectra, both the density distribution and the total mass of the ejecta may be constrained.[5] At IR and radio wavelengths, free electrons scatter off ions without being captured: That free-free process, which dominates emission and absorption, keeps nova ejecta opaque to IR and radio light even after they become transparent to visible light. For typical expected densities and for temperatures of 10 000 K, nova ejecta emit free-free radio emission from opaque ejecta for several months (see figure 2). During that time, the angular diameter of the ejecta increases steadily, so the flux of radio and IR photons increases as the time after ejection squared. Knowing the radial velocity of expansion from spectroscopy and assuming that the nova is spherically symmetrical, researchers can infer the distance to the nova. Eventually the ejecta become transparent even to IR and radio emission.

Box 1. Changes in white dwarf mass

In binary systems that host nova eruptions, accretion plays multiple roles. Between eruptions, it is an important, sometimes dominant source of luminosity and a source of additional mass for the white dwarf. During eruptions, previously accreted material becomes the source of fuel for the thermonuclear runaways (TNRs). The white dwarf therefore gains mass between successive eruptions and loses mass during nova eruptions as the energy of the event ejects the accreted matter. So over many nova cycles, do the white dwarfs gain or lose mass? The answer obviously determines the long-term future of the binaries, which includes the possibility that some become type Ia supernovae.

Theoretically, a key consideration in answering the question is mixing processes. TNRs in novae are fusion reactions, either a carbon-nitrogen-oxygen cycle or an oxygen-neon-magnesium one, and mixing between the white dwarf's envelope and its core material can alter the strength of the TNR. How and how much core material mixes is a matter of debate. Overabundances of elements such as nitrogen and neon are often seen in nova ejecta. That observation, suggesting that some core material is ejected, favors mass loss. However, white dwarfs accreting material from red dwarf companions are more massive than those in white dwarf–red dwarf binaries that haven't yet begun the accretion process, which suggests mass gain.

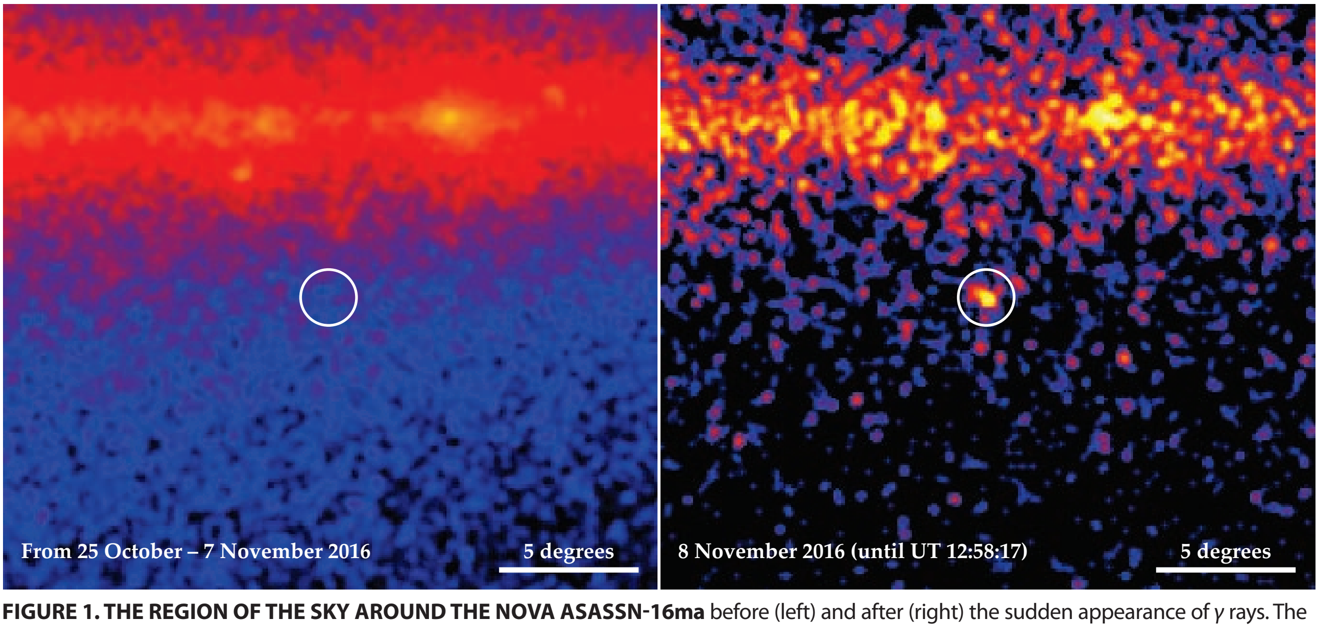

FIGURE 1. THE REGION OF THE SKY AROUND THE NOVA ASASSN-16ma before (left) and after (right) the sudden appearance of γ rays. The images were taken by the Large Area Telescope aboard the *Fermi Gamma-Ray Space Telescope*. (Courtesy of Kwan-Lok Li, Michigan State University.)

The ENova collaboration, which includes the authors, has used the Karl G. Jansky Very Large Array (VLA) in New Mexico, the world's premier radio telescope, to observe more than 20 novae. They are usually well observed using ground-based optical and IR photometry and spectroscopy plus x-ray and UV monitoring with *Swift* and other satellites. Often a game of hurry-up-and-wait is played: When new novae are discovered, early observations must be arranged quickly, and then astronomers must wait months and sometimes years for a nova to first brighten and then fade back to undetectability. The ENova team has published ejecta-mass estimates on four novae so far, ranging from 10^{-5} to 3×10^{-4} solar masses. For several novae, VLA radio observations revealed something even more interesting than their ejecta masses. Flares in radio brightness during the first month after the TNR could be a major clue in the nova γ-ray mystery.

Warm ejecta are complicated

In the simplest case, ejecta from novae are spherically symmetric and were ejected all at once at the time of the TNR. They have a simple density structure such that $\rho \propto r^{-2}$, where ρ is density and r is the distance from the white dwarf, which results from the spread in velocity at the time of ejection, and they have a uniform and constant temperature. Real novae are far more complicated.

Ejecta from novae must vary in temperature both temporally and spatially. If the ejecta are treated as a noninteracting, dynamically expanding shell, one would expect them to adiabatically cool quickly. Observations show that the ejecta remain largely ionized. Otherwise, free-free emission would abruptly cease when the ejecta recombine, an event that has never been seen. Possible sources of heat that have been known for decades include *in situ* decay of radioactive isotopes synthesized during the TNR and irradiation by the central white dwarf, which remains luminous due to continued quasi-steady nuclear burning.

Ejecta from novae have a complicated, clumpy density structure. A *Hubble Space Telescope* image of the remnant of GK Persei (Nova Persei 1901) shows the clumpiness in exquisite detail. In principle, known instabilities can lead to such density inhomogeneity. However, astronomers do not know when during the nova eruption such clumps form and grow. To determine the ejecta mass from radio data, one can parameterize the unknown degree of clumping using a volume-filling factor. Then the data are consistent with a larger range of ejecta masses.

Ejecta may not be expelled promptly during the TNR. In the T Pyxidis nova, the rising part of the radio light curves do not match the expected t^2 dependence if it's assumed that the bulk of the mass was ejected at the onset of its 2010 eruption and TNR. A model with an ejection 50 days after the TNR fits the data well.[6] Similarly, delayed ejection is inferred from the directly imaged expansion history of radio-emitting ejecta in V959 Monocerotis and from x-ray observations of both novae.

Ejecta probably consist of at least two flows that collide with each other. That composition has been learned

Box 2. Nucleosynthesis products

The thermonuclear runaway (TNR) in novae produces copious amounts of radioactive isotopes such as nitrogen-13, beryllium-7, and aluminum-26. Novae could explain the origin of the Milky Way's 1.809 MeV diffuse emission line from the radioactive decay of the ^{26}Al isotope.[15] In the immediate aftermath of the TNR, radioactive isotopes with a half-life of minutes to days are expected to make individual novae transient sources. The 511 keV line is produced by annihilation of positrons from β^+ decay, and the 478 keV line from ^{7}Be decay. Although none have been detected to date, the estimated fluxes from nucleosynthesis models and the sensitivity limits of the current generation of instruments point toward a tantalizingly nearby nova.

The total mass ejected by novae—about 10^{-3} solar masses per year assuming 50 novae—is significantly smaller than that for core-collapse supernovae, which would be 0.1 solar masses per year assuming values of 1 core-collapse supernova per century and 10 solar masses per supernova. Yet novae probably contribute significantly to the galactic chemical evolution of a few select elements or isotopes. One prominent example is lithium, a fragile element whose origin has long been debated. The recent discovery[16] of absorption lines of ^{7}Be in V339 Delphini and ^{7}Li in V1369 Centauri soon after the TNR suggests that ^{7}Be may be created during eruptions in quantities large enough that novae could be a major source of lithium.

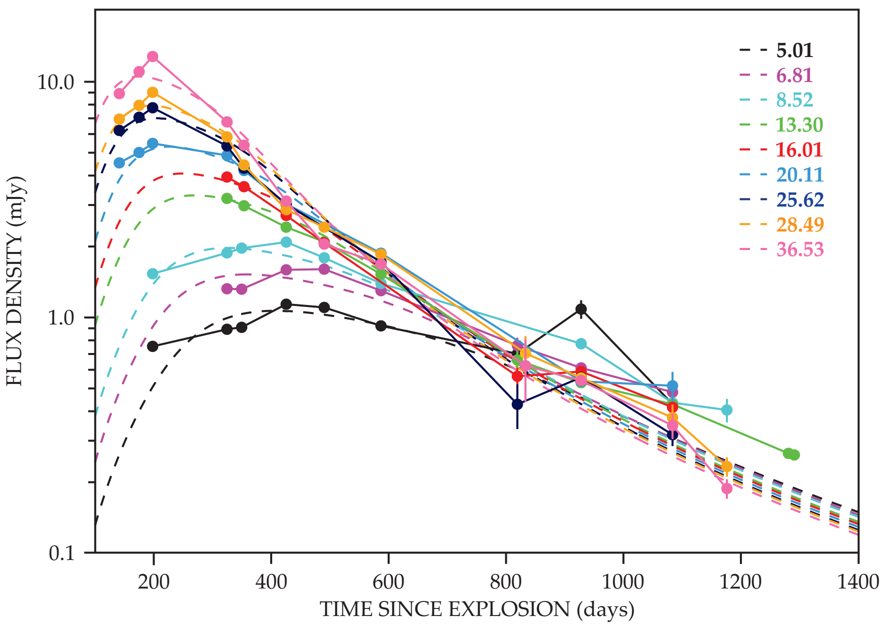

FIGURE 2. THE LIGHT CURVES OF THE NOVA V1723 AQL show the brightness at several gigahertz radio frequencies as a function of time starting 100 days after the eruption of ejecta. The modeled thermal emissions from the expanding ejecta (dashed lines) are similar to observations (solid lines). (Adapted from ref. 14.)

from observations of shocks and from the morphology of ejecta.

A shocking hot phase

In March 2010 a team of researchers using the *Fermi* satellite discovered a transient γ-ray source in the constellation Cygnus. An earlier x-ray observation by *Swift* of that region in the sky confirmed that the mystery object that produced the γ-ray source was a nova called V407 Cygni. Learning that novae can produce γ-ray emission[7] has opened a new field of science for *Fermi* and new avenues of nova research.

To generate γ rays, particles must be accelerated to relativistic energies, which requires a strong shock. Because V407 Cygni has a red-giant mass donor, astronomers believed that the presence of the red giant was the key to producing γ rays. Strong shocks are expected in such cases because a red giant has a massive, slow stellar wind that engulfs the white dwarf. The nova ejecta, therefore, immediately collide with the red giant's wind and create a strong shock at the interface. In fact, researchers have explained certain features of another embedded nova, RS Ophiuchi, using particle acceleration.[8] Once particles are accelerated, γ rays are generated in either the hadronic process, in which accelerated protons collide with matter to create neutral pions that then decay into γ-ray photons, or the leptonic process, in which visible light or IR photons interact with high-energy electrons and attain high energies. No conclusive evidence supports either scenario yet, although theorists may be leaning toward the hadronic model.

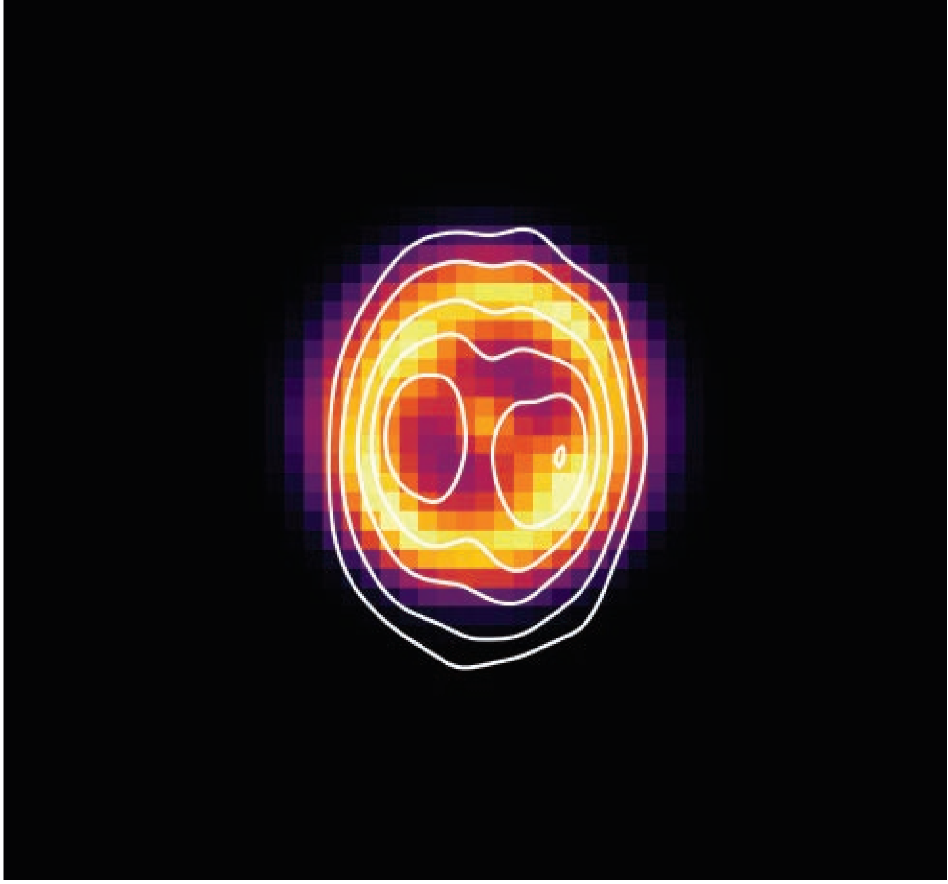

FIGURE 3. THE NOVA V5668 SAGITTARII can be seen by combining optical imagery (color) from the *Hubble Space Telescope* and radio images (white contours) from the Very Large Array telescope. The optical image shows a ring-like structure, and the radio image is dominated by two bright, central knots. Together, the images suggest that the visible nova shape could be a torus viewed from an edge-on perspective. (Courtesy of Justin Linford, National Radio Astronomy Observatory.)

The initial consensus that only novae embedded in the strong wind of the mass donors would emit γ rays was proven wrong in 2012 when γ-ray emissions were discovered from two novae whose red dwarf companion stars lacked strong winds. By now *Fermi* has detected more than a dozen novae. Even novae that are the brightest in γ rays are not much above *Fermi* LAT's detection limit, with a dynamic range in detected flux of about 10. The distances to all galactic novae in the *Fermi* era probably have a range of a factor of 10, or a flux range of a factor of 100 for a single value of intrinsic luminosity. Distance is a major factor in determining which novae can be detected with *Fermi*. Many astronomers now think that most, if not all, novae emit γ rays, although the existing data suggest that some produce more γ rays than others.

Even before the discovery of γ rays, shocks were known to be common in novae. One line of evidence is the early radio emission detected from some novae. For example, the radio emission from the 2010 eruption of V1723 Aquilae became so bright it could not have been produced by the warm ejecta. A shock was required, either to create thermal free-free emission from a large amount of 10^6 K gas or to produce nonthermal emission from accelerated electrons. Another line of evidence is the optically thin, thermal x-ray emission detected from many novae in the 0.5–10 keV band. Shocks with velocities in the 1000–3000 km/s range, which are compatible with the outflow velocities measured using optical spectroscopy, imply plasma temperatures of 10 million K to 100 million K. However, the measured luminosities of the thermal x rays are about 10^{35} ergs/s or less. The fact that the observed γ-ray luminosity is comparable to the observed thermal x-ray luminosity is a huge surprise. Theory predicts that the majority of shock power should remain with thermal particles and that only about 1% of the total shock energy transfers to the accelerated particles. Either the shocks in novae are unexpectedly efficient at accelerating particles, or some more powerful shock is yet to be observed.

It appears that shocks, embedded or not, are ubiquitous in novae and perhaps much more powerful than had been realized. Shocks may even supply some power to the optical emission from a nova. Unlike other astrophysical shocks that accelerate particles, the early shocks in novae arise from modest velocities of about 1000 km/s and the material's high density. Therefore, the thermal x-ray emission behind the shocks can appear as optical emissions because they can be quickly absorbed and reprocessed by the surrounding unshocked ejecta.[9] That model provides a plausible explanation for the behavior of the ASASSN-16ma nova.[10] At optical peak, the γ rays suddenly turned on, as shown in figure 1, and remained strong for nine days. During that period, the γ-ray flux was strongly correlated with the optical flux (figure 1 of reference 10). Such a correlation would be a natural consequence if the γ rays and the optical emission were energized by the same shock whose power fluctuated.

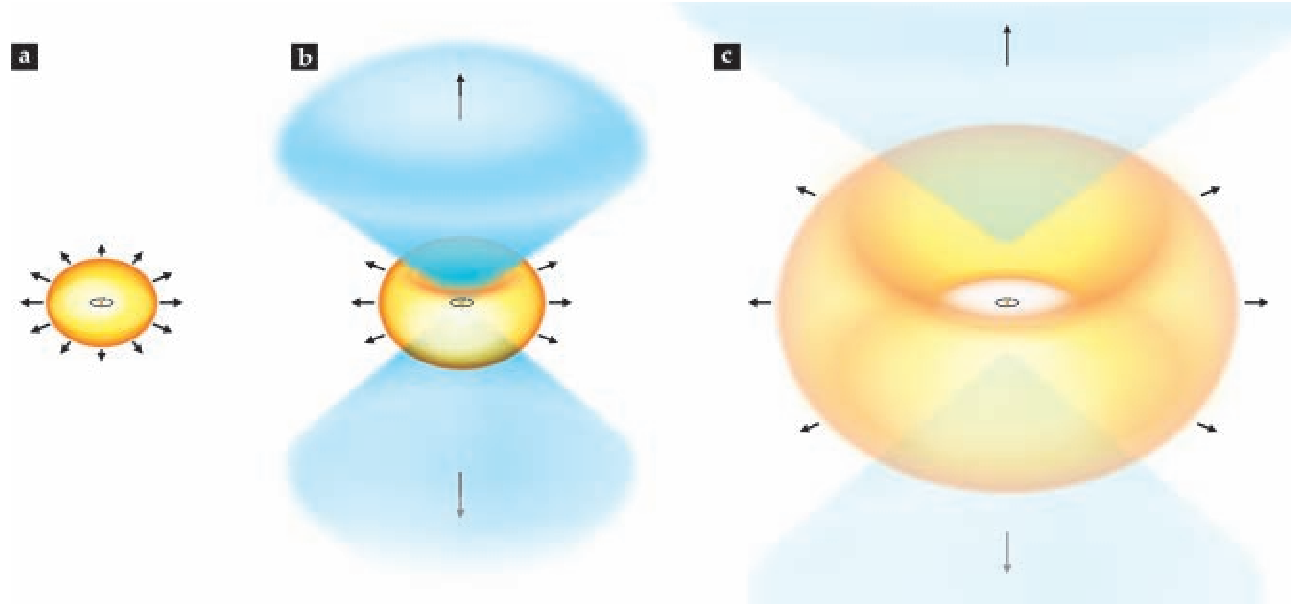

FIGURE 4. A NOVA CHANGES SHAPE OVER TIME. Soon after thermonuclear runaway, an envelope of dense material (yellow) begins to surround the binary system **(a)**, which has the shape of an equatorial torus. **(b)** As the nova explosion continues, the white dwarf energizes fast-moving wind (blue) that flows out toward the low-density conical poles of the torus. Once the wind ceases **(c)**, the outflow detaches from the binary and decreases in density as it expands. The slower-moving material in the equatorial torus remains dense and will be the primary feature observed by radio telescopes. (Courtesy of Theophilus Britt Griswold, NASA.)

The ability of the ejecta to absorb x rays depends on the energy of the x-ray photon. Lower-energy x rays are more easily absorbed. The *NuSTAR* satellite is the first focusing x-ray telescope in orbit searching for x rays above 10 keV and has the best chance of detecting x rays from novae soon after an eruption, when the emission region is located deep inside the ejecta. One study successfully detected the nova V5855 Sagittarii from x rays using *NuSTAR* concurrent with the γ-ray detection by *Fermi*.[11] However, a puzzle still remains: The x-ray luminosity of the deeply embedded shock is still inadequate to explain the γ-ray luminosity unless the shock is unexpectedly efficient at particle acceleration.

Ejecta morphology

Direct imaging of the ejecta from novae is a challenging task. They are bright shortly after the TNR and fade over time. During the early period when novae are bright, their angular scales are modest. For a nearby nova, like many of the ones detected with *Fermi*, the ejecta will have a radius of just 0.1 arcsec one year after the start of the eruption. Ground-based optical imaging of novae sometimes shows spatially resolved nova shells on arcsecond scales as much as a century after the TNR, but only after the shells have expanded for several years or more. Direct imaging within a few years of a nova eruption requires the highest spatial resolutions available, often using *Hubble*, and radio observations with the VLA (see figure 3) and very long baseline interferometry.

Many nova shells are clearly elongated rather than circular. Radial velocity studies of optical-emission-line profiles also show evidence of structures, such as bipolarity and an equatorial ring. One likely origin of the nonspherical shape is that the ejecta are influenced by the binary companion.[12] The difficulty of that interpretation is that fast outflows typical of nova eruptions are less susceptible to the influence of the companion star because they spend little time in the immediate vicinity of the binary, where the effect is large.

When detailed imaging is feasible, such shapes as an equatorial torus and polar cone are often seen, sometimes with additional structures. Simulations that include the effect of binary motion can re-create such morphology at least in broad outline. Radio observations of the V959 Monocerotis, one of the novae that were detected with *Fermi*, helped uncover its structure.[13] Radio data from the VLA trace the warm ejecta, which appeared elongated in the east–west direction four months after the eruption when the fast, biconical wind dominated the radio image.

Two years after the eruption of V959 Monocerotis, the wind

Box 3. Dust in novae

Nova ejecta have warm (10 000 K), hot (greater than 10 million K), and cold phases (1000 K). About 20% of all novae show dips in their optical light curves and an associated excess in the IR. Those properties are evidence of the transient creation of dust along our line of sight, dust that absorbs much of the visible light from the novae and reradiates the energy in the IR. Other novae show IR excess but no optical dips. That situation can be explained by dust that is out of our line of sight, perhaps because dust is preferentially formed near the orbital plane of the host binary. Stony Brook University's Spectral Atlas of Southern Novae database[17] contains example light curves of each. For dust grains to form and grow, the ejecta must be cold and relatively dense. Dust formation may be the consequence of the same shocks used to explain γ-ray emission from novae. Dust grains would be difficult to form without the high-density regions created by novae.[18]

emission faded and revealed an equatorial torus. The rendition in figure 4 shows the ejecta elongated in the north–south direction. In higher angular-resolution images, only the nonthermal emission from compact regions at the interface between the slow torus and the fast wind can be seen, which suggests that the γ-ray-producing shocks developed at that interface. It seems plausible that all novae share the torus and cone structure, and we have been using that framework as the working hypothesis to explain the particle acceleration in novae.

Shocks raise new questions

Where will nova research go? The *Fermi* γ-ray observatory and the upgrade of the VLA radio facility led to the discovery of powerful, particle-accelerating shocks in novae. Those shocks suggest potential solutions to long-standing nova mysteries, such as the clumpiness of the ejecta, dust formation (see box 3), bizarre variations in optical-brightness patterns, and observed equatorial torus and bipolar morphologies. But powerful shocks also raise new questions. Why does the TNR lead to multiple, distinct flows that collide? Can the way in which those outflows are established help explain the large white-dwarf masses found in some interacting binary stars or shed light on what fraction of accreting white dwarfs could become type Ia supernovae? Where are the thermal signatures of the powerful shocks?

One near-future development that will help address those questions is determining accurate distances to novae using data from the European Space Agency's *Gaia* mission. Upcoming time-domain surveys will also uncover novae more efficiently. The next generation of x-ray observatories, including the High-Energy X-Ray Probe (HEX-P), a potential successor to *NuSTAR*, will be capable of diagnosing more shocks even closer to the time of their formation. Future radio telescopes will have higher sensitivity and higher angular resolution to capture the morphology of expanding nova ejecta in greater detail. Those observatories and other new astronomical facilities of the next decade will provide more answers and probably even more questions.

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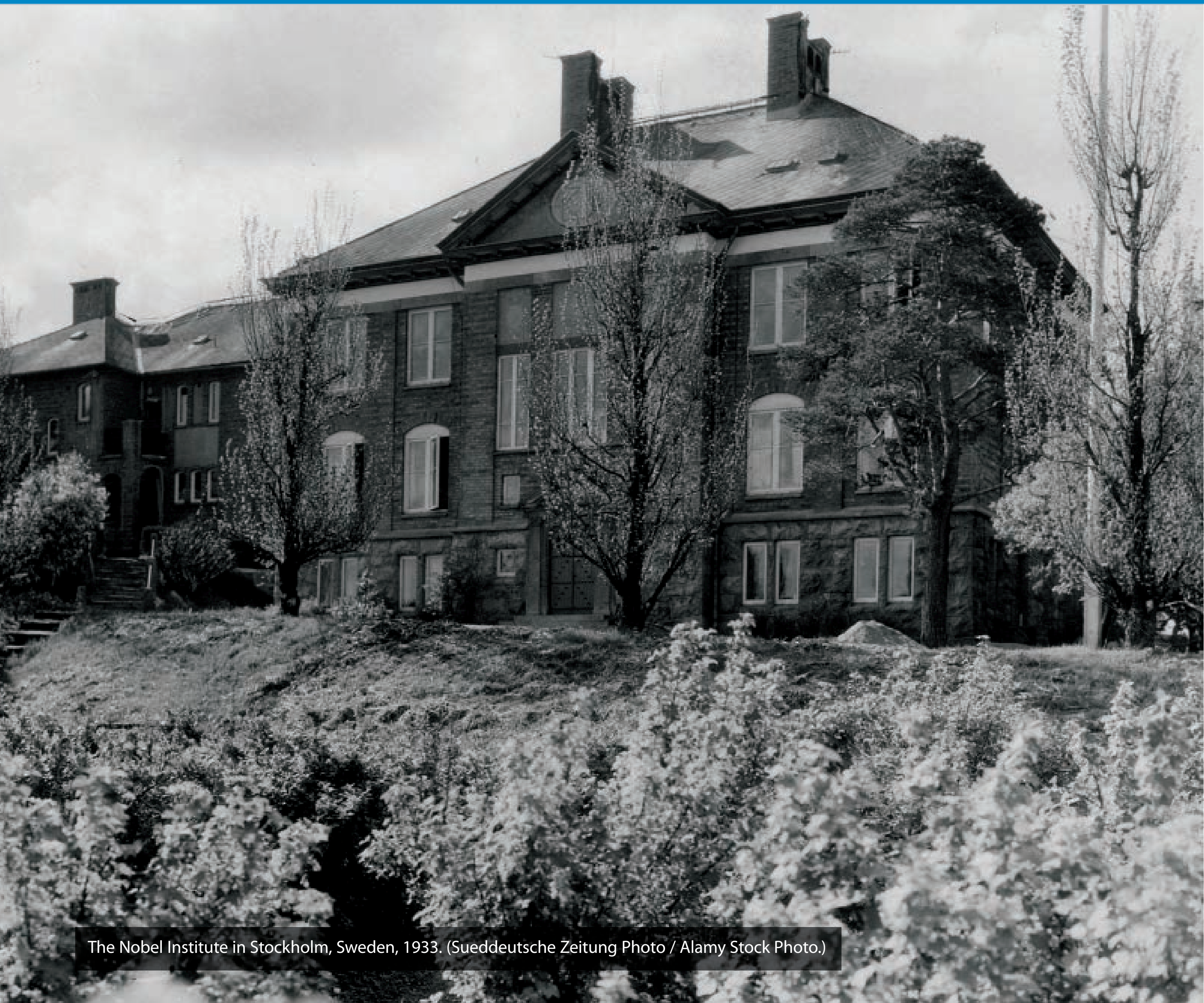
Paul Dirac and the **Nobel Prize in Physics**


The Nobel Institute in Stockholm, Sweden, 1933. (Sueddeutsche Zeitung Photo / Alamy Stock Photo.)

Mats Larsson is a professor in the department of physics at Stockholm University and a member of the Royal Swedish Academy of Sciences. **Alexander Balatsky** is a professor of physics at the Nordic Institute for Theoretical Physics in Stockholm and at the University of Connecticut in Storrs.

Mats Larsson and Alexander Balatsky

Despite the elegance of Paul Dirac's theoretical work, the Nobel Committee nearly passed him over for the prize—until a timely experiment confirmed one of his predictions.

Alfred Nobel's will left only a few criteria for the prizes he created. All five prizes were to be given to "those who, during the preceding year, have conferred the greatest benefit to humankind." For physics, that meant more specifically "the person who made the most important discovery or invention in the field of physics."[1] When the first physics prize was awarded to Wilhelm Röntgen in 1901 for the discovery of x rays, no one could deny that he met the criteria. The nominators overwhelmingly supported Röntgen, and the nomination system has remained essentially unchanged since.

The Nobel Committee for Physics, however, has not always been as unanimous as it was when it chose its first recipient. In the early 20th century, theoretical discoveries in physics were often particularly problematic. Committee members were comfortable awarding the prize to a theorist whose work had clear experimental confirmation; Niels Bohr, whose model of the hydrogen atom matched hydrogen's well-known atomic spectrum and predicted the Rydberg constant, is one example. In contrast, the committee could never unanimously agree that Albert Einstein's special and general theories of relativity had been experimentally and observationally confirmed.[2] Einstein was awarded the 1921 Nobel Prize for his work on the photoelectric effect, but never for one of the most profound theories in the history of physics.

Discoveries in theoretical physics also caused complications for the committee when quantum mechanics (QM) emerged. On 9 November 1933, the Royal Swedish Academy of Sciences announced that the Nobel Prize in Physics for 1932 would go to Werner Heisenberg and the 1933 prize would be shared between Erwin Schrödinger and Paul Dirac (see figure 1). When that announcement was made, three years had elapsed since a physics Nobel had been awarded, the longest peacetime gap in its history. That gap reflects the committee's struggle to come to grips with the new QM. Dirac in particular seemed destined to share Einstein's fate of missing a Nobel Prize for his most important contribution—until experimental confirmation arrived at just the right moment.

The early history of quantum mechanics

Despite the success of the Bohr model and later improvements by Arnold Sommerfeld, it was clear that even the relatively simple spectrum of the helium atom was impenetrable to the

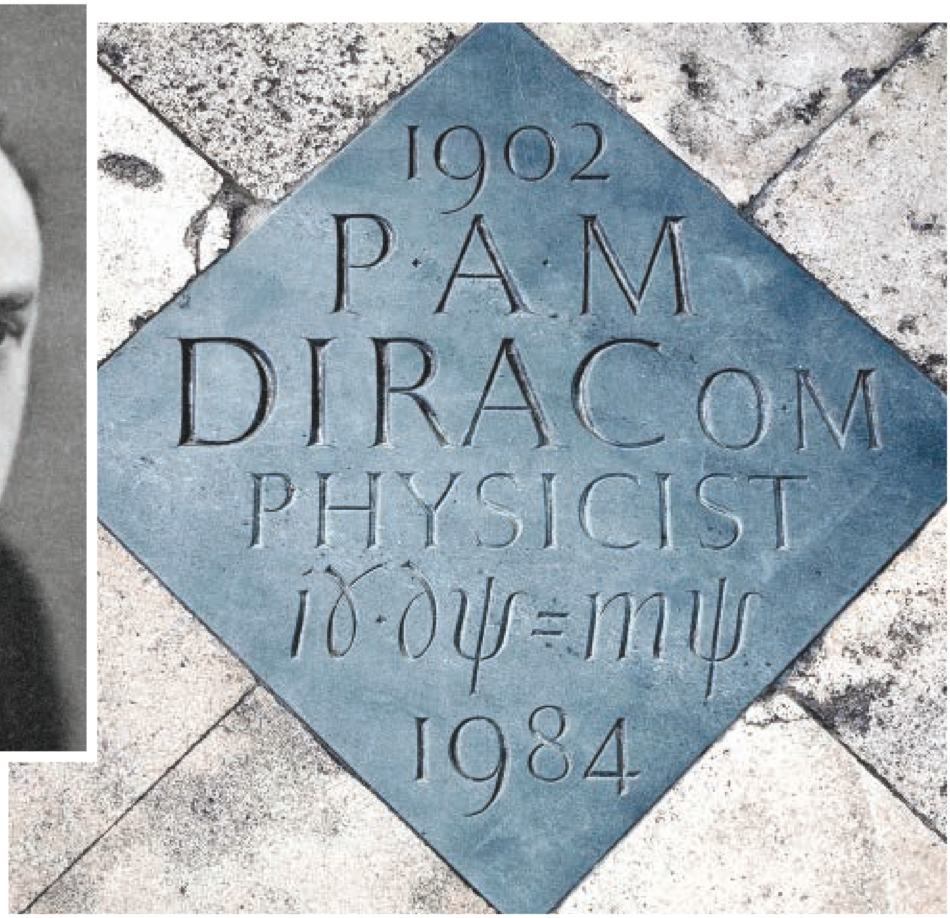


FIGURE 1. PAUL DIRAC (LEFT) AND HIS FAMOUS EQUATION (RIGHT). Dirac's memorial at Westminster Abbey in London includes a version of his Nobel Prize–winning wave equation. "OM" stands for Britain's Order of Merit, which is awarded for distinguished service and is restricted to 24 living members. (Photograph at left by A. Bortzells Tryckeri, courtesy of the AIP Emilio Segrè Visual Archives, E. Scott Barr Collection, Weber Collection; photograph at right published with kind permission of the Dean and Chapter of Westminster Abbey.)

QM developed and applied between 1900 and 1925. Heisenberg was the one who took the first, bold step of formulating a new QM by throwing the nonobservable Bohr atomic orbits overboard. Instead, Heisenberg's QM was based on relationships between observables, such as position and momentum for an oscillator. Heisenberg's groundbreaking paper[3] was received by *Zeitschrift für Physik* on 29 July 1925 and published in December.

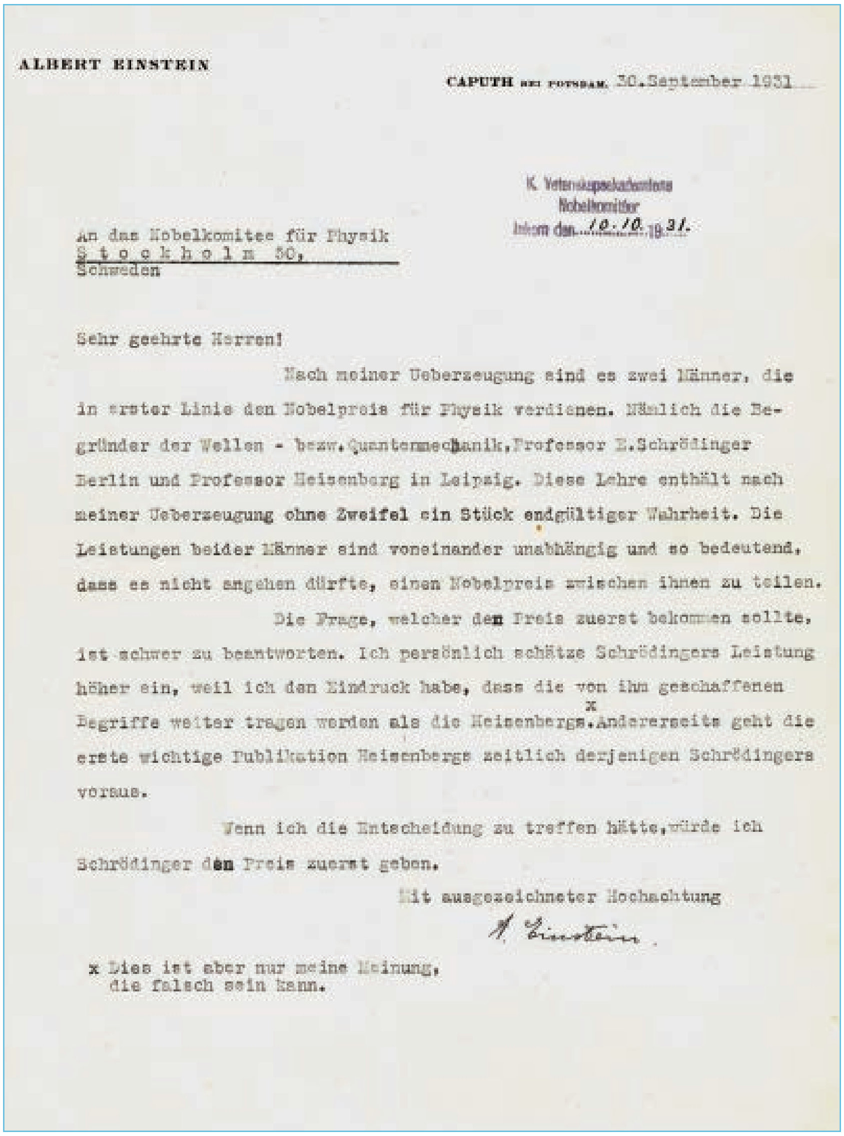
Dirac, then a doctoral student at the University of Cambridge, learned about the paper in advance of publication through his adviser Ralph Fowler, whom Heisenberg visited on his trip to the UK during the summer of 1925. Later that year Dirac came up with his own mathematical formulation of Heisenberg's QM.[4] Meanwhile in Germany, Max Born, Pascual Jordan, and Heisenberg were also working on a mathematical formulation to represent observables with matrices. In Austria, Schrödinger was inspired by Louis de Broglie's concept of the electron's wave nature and formulated his own wave mechanics.[5]

However, neither Heisenberg's matrix mechanics nor Schrödinger's wave mechanics incorporated the special theory of relativity. Another problem was that electron spin had been incorporated into the nonrelativistic quantum equations ad hoc, which resulted in a workable theory that could explain atomic spectra but provided no insight to the origin of spin.[6] It was Dirac who took the decisive step[7] in 1928. His bold idea of writing the wave equation in a relativistic invariant form that was linear in time had a profound impact on physics. That brilliant mathematical insight led to predictions of electron spin and magnetic moment without any ad hoc assumptions. By going from scalar equations to a matrix form, Dirac also introduced the beautiful mathematical formalism that preserves Lorentz invariance:

$$i\partial_t\Psi = (c\boldsymbol{\alpha}\cdot\mathbf{p} + \beta mc^2)\Psi.$$

The introduced matrices $\boldsymbol{\alpha}$ and β, now named after Dirac, act on the wavefunction of the electron. The electron can be written as a four-component spinor: two components for it as particle and antiparticle, and two components for its spin as a fermion. For massless particles, $m = 0$ and the relationship between energy and momentum, the Dirac dispersion, is $E = cp$. Subsequent extensions by Hermann Weyl and Ettore Majorana led to representations that are relevant for modern condensed-matter realizations of Weyl and Majorana fermions.

The seed of the prediction for the antiparticle is apparent from this equation. If the wavefunction of the observed electron required only two components with spin up and spin down, then why are two "unused" components of the spinor needed? Those unused components correspond to negative-energy solutions. At the time, negative-energy solutions were considered undesirable physics, but they predicted an antiparticle, or a positive electron in the terms of Dirac's day. Dirac's



ALBERT EINSTEIN

CAPUTH BEI POTSDAM, 30.September 1931

K. Vetenskapsakademiens
Nobelkommittér
Inkom den 10.10.1931.

An das Nobelkomitee für Physik
S t o c k h o l m 50,
Schweden

Sehr geehrte Herren!

Nach meiner Ueberzeugung sind es zwei Männer, die in erster Linie den Nobelpreis für Physik verdienen. Nämlich die Begründer der Wellen - bezw. Quantenmechanik, Professor E. Schrödinger Berlin und Professor Heisenberg in Leipzig. Diese Lehre enthält nach meiner Ueberzeugung ohne Zweifel ein Stück endgültiger Wahrheit. Die Leistungen beider Männer sind voneinander unabhängig und so bedeutend, dass es nicht angehen dürfte, einen Nobelpreis zwischen ihnen zu teilen.

Die Frage, welcher den Preis zuerst bekommen sollte, ist schwer zu beantworten. Ich persönlich schätze Schrödingers Leistung höher ein, weil ich den Eindruck habe, dass die von ihm geschaffenen Begriffe weiter tragen werden als die Heisenbergs.x Andererseits geht die erste wichtige Publikation Heisenbergs zeitlich derjenigen Schrödingers voraus.

Wenn ich die Entscheidung zu treffen hätte, würde ich Schrödinger den Preis zuerst geben.

Mit ausgezeichneter Hochachtung

A. Einstein.

x Dies ist aber nur meine Meinung,
die falsch sein kann.

FIGURE 2. ALBERT EINSTEIN'S NOMINATION LETTER, dated 30 September 1931, in which he nominated Erwin Schrödinger and Werner Heisenberg. Einstein wrote, "In my opinion, this theory [quantum mechanics] contains without doubt a piece of the ultimate truth. The achievements of both men are independent of each other and so significant that it would not be appropriate to divide a Nobel prize between them. The question of who should get the prize first is hard to answer. Personally, I assess Schroedinger's achievement as the greater one, since I have the impression that the concepts created by him will carry further than those of Heisenberg. [Here Einstein adds a footnote: This, however, is only my opinion, which may be wrong.] On the other hand, the first important publication by Heisenberg precedes the one by Schroedinger. If I had to decide, I would give the prize first to Schroedinger." (Translation from ref. 2, p. 515. Image courtesy of the Center for History of Science, Royal Swedish Academy of Sciences, Stockholm.)

equation thus led to a clear prediction of antiparticles and antimatter, one of the great triumphs of physics in the 20th century.

Meanwhile, de Broglie was awarded the 1929 Nobel Prize in Physics for "his discovery of the wave nature of electrons," a theoretical achievement the committee was not entirely sanguine about rewarding. As late as 1928, the committee still hesitated because the members felt the experimental evidence for de Broglie's work was not sufficiently strong and rejected him in favor of experimentalist Owen Willans Richardson. One year later, however, the committee was convinced that the experimental demonstration of the wave nature of electrons was solid enough to award the prize to de Broglie.

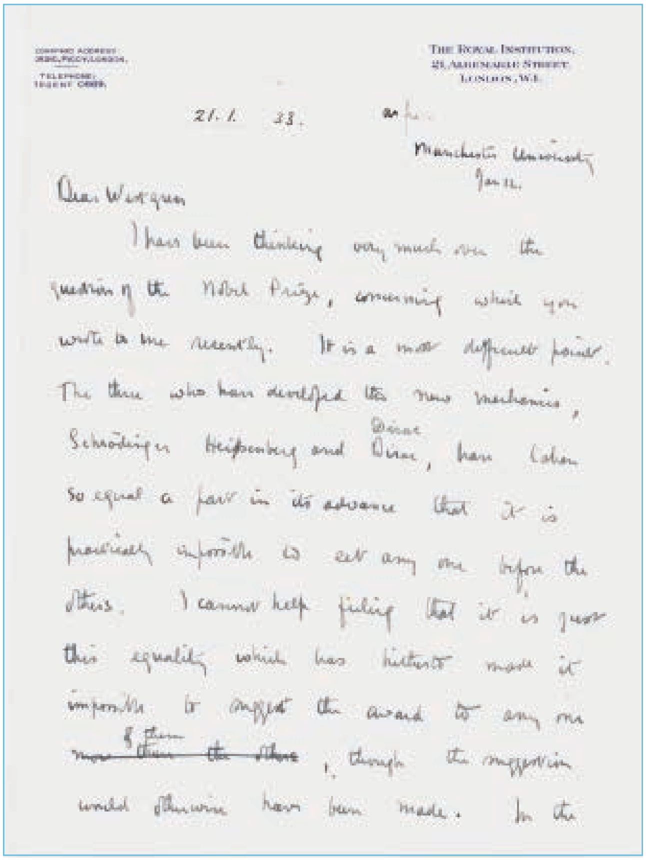
The 1930 physics Nobel went to Chandrasekhara Raman for his work on the scattering of light known as Raman spectroscopy, an experimental achievement that created far less consternation among the committee members. Indeed, they were so confident in the value of Raman's work that they nearly upheld Nobel's wish to reward a discovery from "the preceding year"; Raman made his discovery in early 1928. But as the new decade began, pressure was mounting for the committee to award the prize to work on the new QM.

Nobel nominations 1928–1933

Untangling the reasons behind particular nominations—or their absence—is no easy task. The archives of the Nobel Prize in Stockholm are closely held, and access is granted selectively. Material older than 50 years is open, but only by application and only to historians of science. Newer material is available only to elected members of the Royal Swedish Academy of Sciences.

Furthermore, in contrast to the present-day practice of asking the international physics community to submit confidential expert reports about nominees, in the first six decades of the physics prize, the reports were mainly written by members of the committee and always in Swedish. The reports concerning the Nobel Prize nominees in 1932 and 1933, for example, were mostly written by committee member Carl Wilhelm Oseen, director of the Nobel Institute for Theoretical Physics in Stockholm. The international physics community is visible in the early 1930s only through the nomination letters, which were obviously important but varied in their level of detail.

If we look at nominations from the early 1930s, the following picture emerges. Between 1928 and 1933, the period when the committee was under the most pressure to choose a prize recipient who had worked on the new QM, Schrödinger received 41 nominations; Heisenberg, 29; and Dirac, just 3. The most interesting nominations came from two of the founding fathers of QM, Bohr and Einstein. Writing in Danish, Bohr nominated Heisenberg, arguing that he should be first in line to be recognized for the development of QM. He placed Schrödinger second behind Heisenberg, and never mentioned Dirac at all.[8]

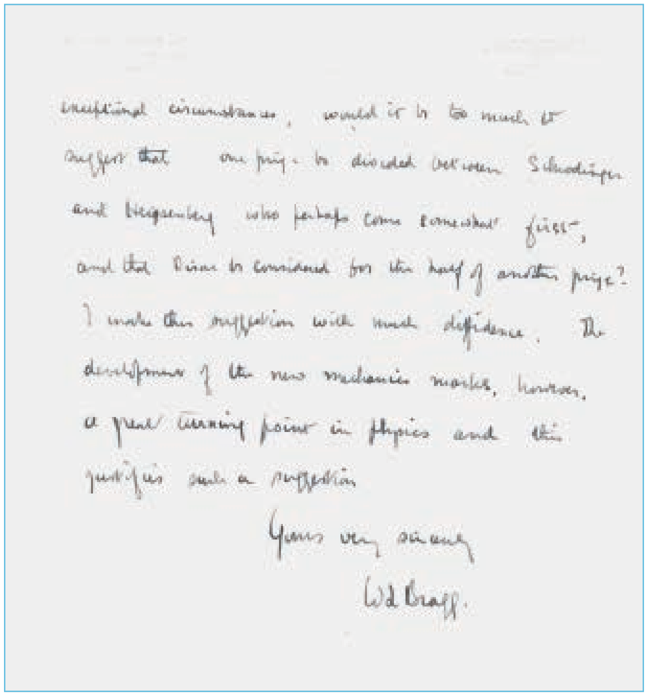

THE ROYAL INSTITUTION,
21, ALBEMARLE STREET,
LONDON, W.1.

21.1.33.

as from Manchester University

Dear Westgren

I have been thinking very much over the question of the Nobel Prize, concerning which you wrote to me recently. It is a most difficult point. The three who have developed the new mechanics, Schrödinger Heisenberg and Dirac, have taken so equal a part in its advance that it is practically impossible to set any one before the others. I cannot help feeling that it is just this equality which has hitherto made it impossible to suggest the award to any one of them ~~more than the others~~, though the suggestion would otherwise have been made. In the


exceptional circumstances, would it be too much to suggest that one prize be divided between Schrödinger and Heisenberg who perhaps come somewhat first, and that Dirac be considered for the half of another prize? I make this suggestion with much diffidence. The development of the new mechanics marks, however, a great turning point in physics and this justifies such a suggestion

Yours very sincerely
W L Bragg.

FIGURE 3. WILLIAM LAWRENCE BRAGG'S NOMINATION LETTER, dated 21 January 1933. It is addressed to "Westgren." Arne Westgren was the secretary of the Nobel Committee for Physics from 1926 to 1943. (Ref. 10; courtesy of the Center for History of Science, Royal Swedish Academy of Sciences, Stockholm.)

Einstein's nomination letter, shown in figure 2, was written from his summer house outside Berlin and is noteworthy in several ways.[9] Einstein was not very active as a nominator, but when he did nominate someone, he had the committee's ear. According to his letter, two men stood at the front of the line for a QM Nobel: Schrödinger and Heisenberg. They had worked independently, and Einstein argued that their work was of such importance that a shared prize should not be considered. Forced to make a recommendation about who should receive the prize first, Einstein put Schrödinger slightly ahead of Heisenberg. Once again, Dirac was not mentioned and, in fact, was never nominated by Einstein.

The date of Einstein's letter, 30 September 1931, is peculiar. It was just barely a month before the Royal Swedish Academy of Sciences was scheduled to announce the 1931 prize. The deadline for nominations, 31 January, had long since passed. Einstein must have known his letter would not count as a nomination for 1931, only for 1932. We can only speculate about his motivation for sending the letter off-cycle, but there seems to have been a growing realization among physicists that the committee ought to acknowledge the new QM.

With such a large number of nominations for Heisenberg and Schrödinger, including from both Bohr and Einstein (albeit a late one), why not award the prize to one or both of them? And why did no one mention Dirac? The committee's problem was how to reconcile a prize for the development of QM with Alfred Nobel's will, which required a "discovery" or "invention" in the field of physics. Oseen, the only theorist on the committee, seems to have particularly struggled with that quandary. True, the new QM had systematized vast swaths of data in atomic physics, but had it led to any new experimental discoveries? In a report to the Nobel Committee dated 16 March 1929, Oseen's conclusion was "no."

Swedish chemist Theodor Svedberg, who had received the 1926 Nobel Prize in Chemistry, tried to help his physics colleagues by nominating Heisenberg in January 1930 for his work on the allotropic forms of hydrogen. In 1927 Heisenberg had predicted that molecular ortho-hydrogen (parallel nuclear spins) should be three times as abundant as para-hydrogen (antiparallel spins), and in 1929 the prediction was experimentally verified. That work was too close to chemistry for the members of the physics prize committee, but the citation for Heisenberg's Nobel Prize mentions the allotropic forms of hydrogen.

Unable to agree on a prize for either Heisenberg or Schrödinger, but also unable to find candidates they preferred, the committee members ultimately decided to postpone awarding the 1931 physics prize. When deliberations for the 1931 and 1932 prizes resumed, they were still ambivalent about their most-nominated candidates, but support was building. Erik Hulthén, an experimentalist whose specialty was molecular spectroscopy, argued that there were now many experimental results, in particular for diatomic molecules, that could only be satisfactorily explained with the new QM. He also emphasized connections between phenomena in nuclear physics, such as radioactivity, and Heisenberg's uncertainty principle.

Oseen, on the other hand, insisted that the new QM was nonrelativistic—an inexcusable omission, in his view. Dirac's theory was relativistic, but Oseen thought it had insurmountable problems—namely, a lack of experimental verification. At the same time, the committee was still unable to identify anyone else who was more worthy of a Nobel Prize than Heisenberg and Schrödinger. Once again, the decision was postponed. The Nobel Prize for 1931 would therefore never be awarded; a prize can only be reserved until the following year.

Experimental confirmation

Before 1933 Dirac received only one Nobel nomination, in 1929 by Hans Thirring at the University of Vienna. In 1933 he received two. One was from Czesław Białobrzeski at the University of Warsaw, who also nominated Heisenberg. The other was from William Lawrence Bragg, recipient of the 1915 Nobel Prize in Physics. Bragg's nomination letter[10] explicitly put Dirac on equal footing with Heisenberg and Schrödinger (see figure 3), and it prompted Oseen to write a long report[11] about Dirac, which he submitted to the committee in March 1933.

Oseen could not accept Dirac as an equal to Schrödinger and especially to Heisenberg. Was Dirac a scientific innovator of the same caliber as Nobel recipients Max Planck, Einstein, and Bohr? For Oseen, the answer was definitely no. He compared Dirac's contributions with those of Born and Jordan in Germany. Their efforts to give a mathematical framework to Heisenberg's QM were never seriously considered worthy of a Nobel Prize. Furthermore, Dirac's 1928 paper had predicted not only the real physical states but also negative energy states in which the electron had positive charge. That charge, though, had never been observed. It is clear from Oseen's report that Dirac was not initially a contender for either the 1932 or 1933 prize. He had done work that was correct but not first, and when he was first, he was not correct—or at least not confirmed.

But a remarkable finding was about to paint Dirac's work in a new light. The same month that Oseen submitted his report about Dirac to the committee, US physicist Carl Anderson published a paper in *Physical Review* about his discovery of the positive electron.[12] Dirac's theory had now made a prediction that had been experimentally verified.

The committee members did not change their stance immediately. At the committee's June meeting, Heisenberg and Schrödinger were shortlisted, but Dirac was not. Anderson's discovery, however, was stirring excitement among physicists. That summer, J. Robert Oppenheimer and Milton Plesset wrote a letter to *Physical Review* in which they suggested that pairs of negative and positive electrons could be created in the vicinity of a nucleus.[13] By applying Dirac's relativistic electron theory, they calculated the probability of pair production as a result of the gamma-ray irradiation of matter. The results were in fairly good agreement with experimental results published by Patrick Blackett and Giuseppe Occhialini earlier that year.[14] Now Dirac's theory had both qualitative confirmations and an approximate quantitative confirmation.


SVENSKA DAGBLADET

Fyra Nobelpristagare utsedda

Fysikprisen till W. HEISENBERG, Leipzig. E. SCHRÖDINGER, Berlin. P.A.M. DIRAC, Cambridge.

Litteraturpriset till IVAN BUNIN.

Luthers släkt lever i Sverige

Japan har kallat hem ambassadören i Moskva

Det hålles för troligt att han ej återvänder. Tre divisioner ha beordrats till Korea.

LÄGET YTTERST SPÄNT

Heisenberg varm vän av Skandinavien

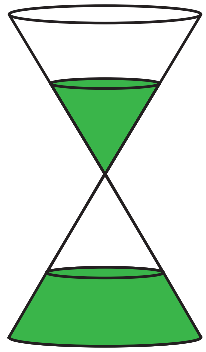
Schrödinger återvänder ej till Tyskland

FIGURE 4. THE FRONT PAGE OF *SVENSKA DAGBLADET* ON 10 NOVEMBER 1933, announcing Paul Dirac, Werner Heisenberg, and Erwin Schrödinger as Nobel laureates in physics. (Courtesy of *Svenska Dagbladet*.)

A late addition

Those developments prompted Oseen to write an addendum to his March report for the committee's meeting in September, at which it was expected to make its recommendations for the 1932 and 1933 Nobel Prizes in Physics. On 25 September 1933,

INFLUENCE OF DIRAC'S IDEAS



In the modern vernacular, the Dirac equation is a scientific meme: It is a single quantum of knowledge that had no precedence but rapidly gained wide acceptance. It took less than five years from publication of Paul Dirac's 1928 paper to the Nobel Prize decision.

As is often the case with truly insightful ideas, Dirac's equation has a wider range of applicability than even Dirac himself initially realized. That the wavefunction is acted on depending on which direction particles move by matrices α_x, α_y, *and* α_z for the directions *x*, *y*, and *z* turns out to be a simple yet very powerful idea. Physicists have found that a similar mathematical structure governs the behavior of many materials. Researchers have discovered a rapidly expanding list of materials and systems that can be effectively described using Dirac's elegant equation.

Condensed-matter physics in particular has recently seen a resurgence of research on topological nodal materials, including graphene, topological insulators, and the unconventional superconductors that are now called Dirac materials. DMs are those in which the properties of the excitations are physically identical to Dirac fermions. The crossing, or pinch point, also known as the Dirac node, is what makes both DMs and Weyl materials (the simplest irreducible three-dimensional version of a DM) respond to external fields and defects in a universal way.

The left-hand figure is an illustration of the Dirac dispersion and node for electron–hole excitations in a DM, where μ_e is the chemical potential for the electron and μ_h is the chemical potential for the hole. The pinch point creates an inverted particle distribution in driven DMs similar to the inverted mass distribution in an hourglass, as shown in the right-hand figure. The pinch point makes the DM qualitatively different from a conventional metal.

The range of those new nodal materials goes far beyond graphene. There are entire classes of 2D and 3D materials, Weyl and Dirac semimetals, and even unconventional superconductors. We also see the extensions of the concept to bosons like magnon and phonon DMs, something not seen in high-energy physics since the Dirac equation was originally proposed for fermions. Books and reviews published on DMs illustrate their new importance for physicists.[17] If the past is any predictor, we are sure the list of applications will grow.

the committee recommended that Heisenberg should receive the 1932 reserved prize and that Schrödinger and Dirac should be jointly awarded the 1933 prize "for the discovery of new productive forms of atomic theory." In Oseen's undated amendment, Dirac's name was inserted by hand into the typewritten recommendation.[15]

The Royal Swedish Academy of Sciences followed the committee's recommendation when it made the final decision on 9 November 1933 (see figure 4). In committee member Henning Pleijel's presentation speech on 10 December, he said to Dirac, "The experimental discovery of the existence of the positron has in a brilliant way confirmed your theory."[16] The Swedish newspaper *Dagens Nyheter* reported the next day, "Then followed [after Heisenberg], one after the other, professor Schrödinger and young professor Dirac, who staggered down [the stairs] in a real old-fashioned professor's white tie. But this didn't prevent mama Dirac from being somewhat proud where she was sitting and stretching herself on the third row behind the high-sounding foreign ministers."

We now know that Dirac's elegant equation has applications in a wide range of fields, including materials science (see the box). Bragg was the first to suggest that Heisenberg, Schrödinger, and Dirac were equals as physicists. Posterity has confirmed his claim—and for some of us, Dirac is perhaps first among those equals.

We are thankful to the Royal Swedish Academy of Sciences for access to its Nobel archives and to Karl Grandin, head of the archives, for valuable comments. We are grateful to Konrad Kleinknecht for comments. Alexander Balatsky's work was supported by the Villum Centre of Excellence for Dirac Materials, grant 11744, and Knut and Alice Wallenberg Foundation grant 2013.0096.

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PT

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A Zen-like journey through the mysteries of physics

"What is the sound of one hand clapping?" That simple riddle, with its multitude of possible correct responses, is perhaps the most familiar example of a Zen koan, a short parable designed to provoke the listener to pause, reflect, and perhaps alight on deep and subtle truths. A koan does not provide an answer; it poses a question that highlights the tension between multiple points of view. It is up to the listener to seek the answers through meditation on the meaning of the tale.

In *Cosmological Koans: A Journey to the Heart of Physical Reality*, theoretical physicist and cosmologist Anthony Aguirre uses a series of koan-like vignettes to explore questions at the forefront of theoretical physics and cosmology and some of their profound implications.

The basic style of the koan should be familiar to students of physics. Modern physics, like Zen Buddhism, often comprises counterintuitive and abstract ideas. In physics, those ideas are typically contained in tiny equations replete with subtle implications. Learning the equations can often be accomplished in less than an hour, but understanding the full depth of their consequences can take more than a lifetime. A physicist builds intuition into mysterious and abstract topics by working through examples to extract their exquisite lessons.

Cosmological Koans

A Journey to the Heart of Physical Reality

Anthony Aguirre

W. W. Norton, 2019. $27.95

Aguirre's book is organized as a fantastical journey set in the 17th century. Each short chapter begins with a brief narrative, written in the second person, describing an eventful moment along the way. The narrative is followed by one or two quotes providing some historical perspective, and the chapter finishes with a discussion of the physical principles or their consequences as illustrated by the events. The prose has a playful, dreamy quality. Aguirre manages to juxtapose the 17th-century journey with 21st-century physics in a way that feels natural and unforced. Through analogies to the journey's events, Aguirre manages to break down even the most complex and abstract ideas into something accessible to a general audience.

That is not to say that the book is easy reading—the wisdom contained in any koan requires thoughtful engagement by the reader. Rather than laying out a deductive chain of reasoning, a typical chapter tends to meander around an idea, developing intuition and deeper understanding and, most importantly, conveying to the reader that the idea represents research that is still in progress. No one can just tell you the answer, because no one knows with complete certainty what the answer is.

The book begins with a discussion of the simplest concepts in physics, then rapidly builds into explorations of relativity and quantum mechanics, which both lead in different ways to the counterintuitive notion that the information available to any observer is necessarily finite. Along the way, Aguirre explores thermodynamics and the tendency of a closed system to move from order toward chaos. Notions of time and quantum causality provide insights into the modern origins of the universe and the possibility that the totality of what we see may represent only a small piece of a larger multiverse spanning all possible universes. *Cosmological Koans* also raises the possibility that we find ourselves with physical laws uniquely suited to our existence precisely because we are present to measure them.

From there, the discussion moves beyond the physics to an exploration of its implications for the nature of consciousness and being. Exposing the inescapable connection between our sense of self and the greater universe completes the circle: The koans are not just a vehicle to explain physics using the language of Zen; they directly connect the two subjects.

This is not a book to devour in one sitting. It is much better savored, with time between chapters to reflect on the messages they convey. *Cosmological Koans* is a journey worth taking for travelers both well-versed in and new to speculative ideas in theoretical physics.

Timothy M. P. Tait
University of California, Irvine

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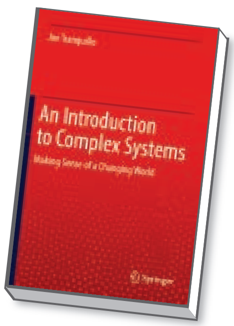
Archaeology is one of the many fields to which complex-systems analysis can be applied.

An encyclopedia of complex systems

The field of complex systems has formally existed for several decades, and many of its founders, including Nobel Prize winner Murray Gell-Mann, came from physics. Yet the field has recently flourished; it is experiencing a rise in practitioners, an expanding number of intriguing problems to address, and a commensurate increase in high-impact publications. In his new book *An Introduction to Complex Systems: Making Sense of a Changing World*, Joe Tranquillo joins a growing body of authors aiming to define complex systems and disseminate the field's most important conclusions to the greater world. The text provides a useful overview of complex systems, with enough detail to allow a reader unfamiliar with the topic to understand the basics. The book stands out for its comprehensiveness and approachability. It will be particularly useful as a text for introductory physics courses.

An Introduction to Complex Systems
Making Sense of a Changing World
Joe Tranquillo
Springer, 2019.
$109.99



Tranquillo's strength is in delivering a vast amount of information in a succinct manner. Unlike Geoffrey West's *Scale: The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies* (2017), Tranquillo's book is not for general audiences. It does not dive deeply into individual subjects the way Mark Newman's *Networks* (2nd edition, 2018) does, nor does it provide a how-to on a specific method, as Steven Railsback and Volker Grimm do in *Agent-Based and Individual-Based Modeling: A Practical Introduction* (2nd edition, 2019). Instead, Tranquillo has written a thorough textbook that gives a useful introduction to complex adaptive systems as a whole field. It can also serve as a quick reference for seasoned practitioners who need a refresher on a particular subject.

The field of complex systems does not fall within any one discipline. Its techniques and concepts are useful for various sciences and for making order out of seemingly disorderly structures and have been applied in physics, economics, biological systems, computer science, mathematics, and my own field of archaeology. Tranquillo, whose background is in engineering, touches on each of those applications in his text and demonstrates that to be a true scholar of complexity one needs to embrace interdisciplinarity. "It is not always clear where one discipline ends and the field of complex systems picks up," he writes in the first chapter. "As an interdisciplinarity field . . . it has inherited tools, processes, ways of thinking, histories, tensions, and world views from other disciplines."

The book is an excellent reference for many of the mathematical formalizations that provide the backbone for complex-systems study. Tranquillo's text displays those formalizations seamlessly, in a way that will be useful for teaching students about the underlying thought processes. Yet, even though math is well-integrated into the text, a reader could skim over the equations and focus instead on the prose without losing much. Tranquillo's presentation will allow mathphobes to be slowly exposed to equations—alongside good explanations—without being forced to read through proofs line by line; thus the book is a useful text for mixed-population undergraduate courses. Those who are looking for a more advanced text that delves deeply into a certain area of complex adaptive systems are likely to find *An Introduction to Complex Systems* a bit thin. However, it is not meant to be an in-depth guide, but rather a survey of the field.

What makes *An Introduction to Complex Systems* stand out is its thoroughness. The book is basically an encyclopedia of complex-systems studies. Need to quickly reference the equation for the first law of thermodynamics? Section 7.1.3. How about measures of information? Section 6.1.4. A reader can find information quickly and efficiently—that is, in my opinion, the book's greatest value. If Tranquillo's text ends up on your shelf, you'll find that you thumb through it regularly for a pithy description of a particular complex-systems approach.

Stefani Crabtree
Santa Fe Institute
New Mexico

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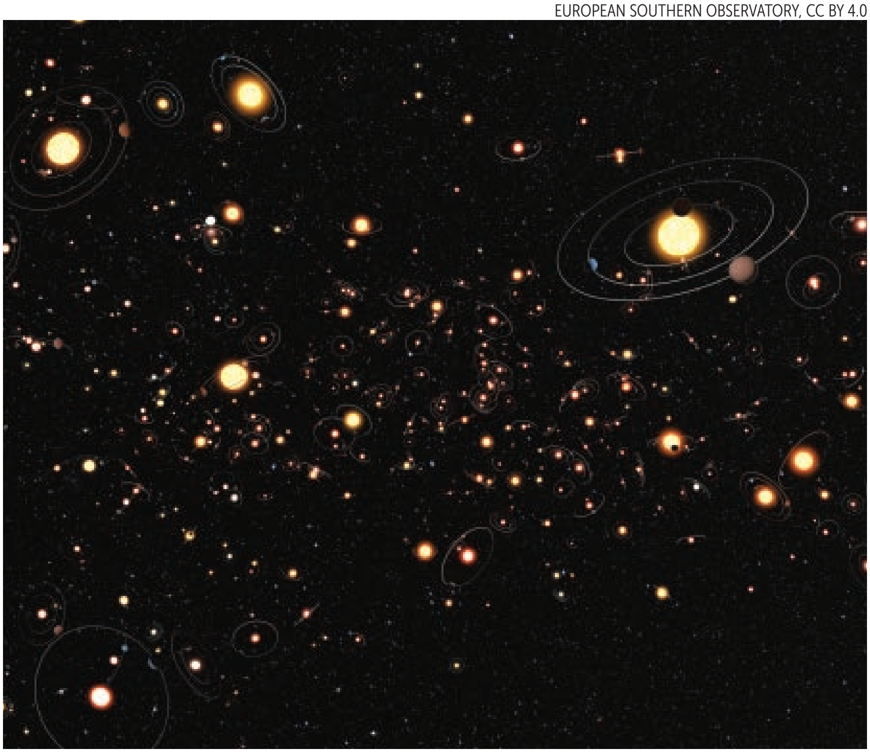
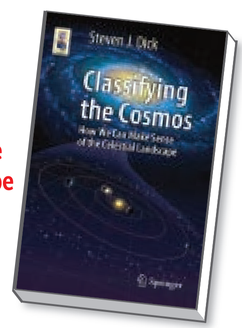


A Linnaean system for the stars

In 1735 Swedish botanist, zoologist, and physician Carl Linnaeus published his 12-page tract *Systema Naturae*. In it, he laid out a system for organizing life forms into a helpful hierarchy of categories—the roots of our modern kingdoms, phyla, families, and species. Astronomy, however, did not benefit from such a definitive moment; its systems for naming and classifying objects developed in fits and starts as new technologies revealed ever more marvelous denizens of the universe. In *Classifying the Cosmos: How We Can Make Sense of the Celestial Landscape*, astronomer and former NASA historian Steven Dick endeavors to bring some order to the cosmic menagerie as we know it today. The result is an important and revelatory work that can be used by researchers, educators, and enthusiasts alike.

Classifying the Cosmos
How We Can Make Sense of the Celestial Landscape
Steven J. Dick
Springer, 2019. $34.99 (paper)



In one sense, *Classifying the Cosmos* offers a comprehensive encyclopedia of celestial objects. Dick adds greater value, however, by providing a thematic architecture for the known inhabitants of the cosmos. His celestial empire consists of three kingdoms—planets, stars, and galaxies—broken down into 18 families, 82 classes, and unnumbered types. Gravity, the key organizing principle, weaves everything together. The more speculative topics of dark matter and dark energy are left to others.

Dick's explanation of planets exemplifies how the classification system works: Planets are fully described in the planets kingdom section, but are also cited as circumstellar objects in the stars kingdom section. Stars, in turn, have their own kingdom but also play key roles in the galaxies kingdom. That sort of overlap makes explicit the hierarchy of matter in our universe. From planets, to stars with planetary systems, to galaxies and their groupings on ever grander scales, Dick unfolds our observable cosmos like the nested, connected, and evolving ecosystem it is.

The author also provides fascinating historical backstories to many of the classes and how they were discovered. For example, he recounts how the ice giant planet Uranus was observed several times in the century that preceded William Herschel's written account in 1781 and how Herschel first described it as a comet rather than a planet. Even more amazing, Galileo Galilei accidently observed Neptune a whopping 234 years before its official discovery by Urbain Jean Joseph Leverrier in 1846. It then took *Voyager 2*'s flybys of Uranus in 1986 and Neptune in 1989 to generate sufficient data for astronomers to conclude that those two planets belonged to a new class of ice giants that differ in size and composition from the gas giants of Jupiter and Saturn.

Dick also wades into continuing controversies, such as the kerfuffle surrounding Pluto's demotion to dwarf planet. He notes the proposal to designate Pluto's similarly massive kinfolk in the Kuiper belt as "Plutoids," a classification that I have been championing in my own writings but, alas, has yet to catch on. Consequently, Dick places Pluto in the dwarf planet class as part of the subplanetary family that includes meteoroids, asteroids, comets, and other small bodies of the solar system.

The author admits that classification does not necessarily imply understanding. Nevertheless, he provides ample descriptions of each class so that the reader can gain a decent understanding of the phenomena associated with them. *Classifying the Cosmos* focuses on the physical nature of each object, rather than on qualities such as appearance or means of observing. For example, he favors differentiating stars not by their colors and corresponding surface temperatures, but by their luminosity classes, as determined by their spectroscopically derived surface gravities and corresponding sizes. The resulting stellar classes of dwarf, subdwarf, subgiant, giant, bright giant, supergiant, and hypergiant make sense in that taxonomic architecture.

Dick's classification system constrains main-sequence stars, also called dwarf stars, to a single class because of their key physical similarity, namely core hydrogen fusion. Thus, 90% of all extant stars fall into just one of his 36 stellar classes. The author then characterizes their wide-ranging masses, luminosities, temperatures, energy-transfer mechanisms, and other properties in only eight pages. I do not wish to complain here, but I do want to note that his treatment favors key physical differences over quantitative demographics.

My biggest concern lies in the galaxy family of the galaxies kingdom. Elliptical, lenticular, spiral, and irregular galaxies all constitute classes in the normal subfamily, and Seyfert galaxies, radio galaxies, quasars, and blazars are classes in the active subfamily. I was surprised by the lack of a comparable starburst galaxy subfamily or class despite numerous mentions; surely such a categorization would be justified based on their unique physical properties. Dick instead discusses starburst galaxies in other classes under the galaxy, intergalactic medium, and galactic systems families.

That minor gripe aside, I found *Classifying the Cosmos* to be thoroughly researched and engaging. It includes ample references to original peer-reviewed articles, the latest mission websites, and well-written general-interest articles by respected science writers. Although the author's tone is mostly informative, he sometimes waxes more lyrical. I especially liked the passage in which he notes that Herschel "likened the heavens to a luxuriant garden, where we see in succession 'the germination, foliage, fecundity, fading, withering, and corruption' of plants, except that in the heavens, we see all stages at once. Whether plants or planets, sunflowers or stars, we see the lifecycle of nature's creations spread before us, awaiting understanding."

The excellent scientific content, beautiful color images, and high-quality printing of this book make it a winner. In the introduction, Dick expresses the hope that his classification effort will be of educational use, "helping students and astronomy enthusiasts understand the place of these objects in the celestial landscape." I would say that he has succeeded most admirably. I would also add that the book will be a handy reference for researchers and communicators of astronomy.

William H. Waller
Rockport, Massachusetts

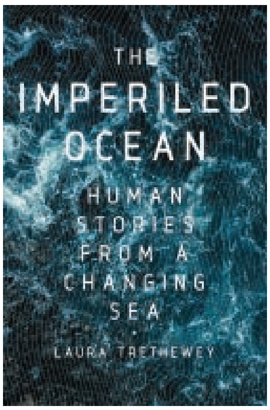
NEW BOOKS & MEDIA

Tumble

Science Podcast for Kids

Lindsay Patterson and Marshall Escamilla, 2019 (Season 5)

Science journalist Lindsay Patterson and music teacher Marshall Escamilla cohost this charming podcast that's aimed at elementary school students. Recent episodes open with a question from a young listener, such as "Do plants feel pain?" or "Why are hurricanes so powerful?" Patterson and Escamilla interview scientists to learn the answer; season 4 guests included climate physicist Suzana Camargo and astronomer Jane Luu. Married collaborators Patterson and Escamilla are engaging and have a warm chemistry, and the 20-minute episode length is a good fit for kids' attention spans. Season 5 began on 4 October, and episodes will be released every other week. —MB



The Imperiled Ocean

Human Stories from a Changing Sea

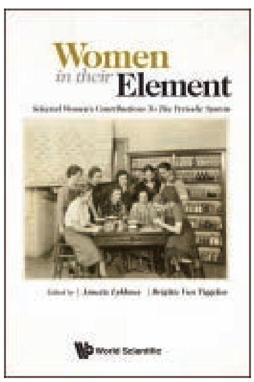
Laura Trethewey
Pegasus Books, 2019. $28.95

"What is going on out at sea?" asks journalist Laura Trethewey in the introduction to her collection of narrative nonfiction, *The Imperiled Ocean*. The answer is a lot: It's a place that people use to earn a living, migrate to another country, inspire creativity, go on adventures, and conduct research. In her first book, Trethewey tells seven stories of what people want from the ocean. The disappearance of a young, ambitious Chilean chef from a luxury liner invites readers to think more deeply about the murky laws that govern the high seas and the safety precautions that people do or don't take. A clash in a small Canadian town between a group of older, mostly impoverished boat dwellers with nowhere else to live and gentrifiers who view that lifestyle as a polluting eyesore illustrates the issues of class and water rights. *The Imperiled Ocean* will appeal to both seafaring types and broader audiences looking for personal stories about universal human experiences. —AL

Women in Their Element

Selected Women's Contributions to the Periodic System

Annette Lykknes and Brigitte Van Tiggelen, eds.
World Scientific, 2019. $128.00



In recognition of the 150th anniversary of the publication of Dmitri Mendeleev's periodic table of elements, chemistry historians Annette Lykknes and Brigitte Van Tiggelen have assembled 38 biographical vignettes that showcase the roles of women in the development of chemistry and the periodic table. Written by authors from all over the world and from various disciplines, the chapters focus on discoveries and important events from the 18th century and earlier to recent times. The goal of *Women in Their Element*, say the coeditors, is both to shed light on the efforts of a group of scientists whose work has often been relegated to the shadows and to reaffirm the collaborative nature of science. —CC

Into the Impossible

Arthur C. Clarke Center for Human Imagination, 2016–present

Want to add an exciting new book to your shelf, hear an interview with Freeman Dyson, or listen to a sci-fi author talk about how she builds her strange new worlds? *Into the Impossible* is exactly what you've been looking for. Clarke Center leaders Sheldon Brown, Brian Keating, Erik Viirre, and Patrick Coleman take turns hosting interviews with scientists, authors, historians, and other exciting thinkers in this eclectic scholarly podcast. Among the recent guests are science fiction author Annalee Newitz, journalist Julian Guthrie, and physicists Paul Steinhardt and Carl Wieman. Half-hour episodes are released roughly once a month. —MB

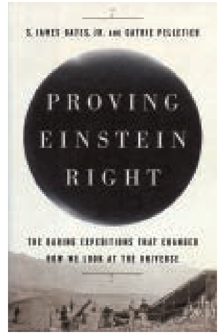
Radio Astronomy Podcast

BBC Sky at Night Magazine, 2016–present

This monthly half-hour podcast about space and astronomy is produced by *BBC Sky at Night Magazine*. News editor Elizabeth Pearson hosts, and *Sky at Night* staff members join her to discuss the magazine's content and news they're excited about. Recent episodes cover India's Moon landing attempt, new findings about Jupiter's atmosphere, and the recent discovery of possible tardigrades on the Moon. Listeners in the UK will also enjoy the tips for stargazing each month. —MB

Proving Einstein Right

The Daring Expeditions That Changed How We Look at the Universe



S. James Gates Jr and Cathie Pelletier
PublicAffairs, 2019. $30.00

In 1911, while working on his theory of relativity, Albert Einstein predicted that light from other stars should be bent by the Sun's gravity. To prove the theory, seven astronomers from four countries spent the next decade traveling the world to try to photograph a solar eclipse, when sunlight is blocked and the stars can be seen. Written by theoretical physicist S. James Gates Jr and novelist Cathie Pelletier, *Proving Einstein Right* recounts the many adventures, hardships, and mishaps that the astronomers and their crew experienced, including the travel dangers wrought by World War I. —CC PT

MATERIALS SCIENCE AND ENGINEERING

Faculty Positions – Open Rank

University of Illinois at Urbana-Champaign

The Department of Materials Science and Engineering (MatSE) at the University of Illinois at Urbana-Champaign is seeking to fill multiple tenured or tenure-track faculty positions in all ranks. We particularly seek candidates with research interests in two priority areas: (1) biological and biomedical materials and (2) metals, in both cases with an emphasis on experimental research. However, candidates with research interests in other areas of materials science and engineering are also encouraged to apply. Senior and mid-career faculty are encouraged to apply, but all qualified candidates will be considered. Faculty members in the department are expected to initiate and sustain a vigorous research program. Successful candidates are expected to demonstrate a strong commitment to undergraduate and graduate teaching, and to diversity, equity, and inclusion through research, teaching, and/or service endeavors. Please visit **https://jobs.illinois.edu** to view the complete position announcement and application instructions.

Applications received prior to November 15, 2019 will receive full consideration.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

Illinois is an EEO Employer/Vet/Disabled - www.inclusiveillinois.illinois.edu

THEORETICAL HIGH-ENERGY PHYSICS FACULTY POSITION

The Department of Physics, Colorado State University, seeks to hire at least one tenure-track faculty member at the rank of Assistant Professor in **theoretical high-energy physics**. Exceptional candidates will be considered for positions with a more senior rank. Candidates whose research complements the CSU program in experimental high-energy and particle astrophysics (HEPPA) are strongly encouraged to apply. Candidates must hold a Ph.D. in physics or an equivalent degree and have a documented potential for outstanding teaching, scholarship, and research. Postdoctoral and/or other substantial experience beyond the Ph.D. is expected. Complete applications consist of a cover letter, detailed CV, descriptions of research plans and teaching interests, and three letters of reference. Your references will be contacted immediately upon submission of application and will receive an email with a link to submit their letter. Applications must be submitted online. For more information,including application instructions, see **https://jobs.colostate.edu/postings/71002**. Applications completed by November 13, 2019 will receive full consideration, but applications will be accepted until the position is filled. Colorado State University is an EO/EA/AA employer and will conduct background checks on all final candidates.

UNIVERSITY OF ALABAMA at BIRMINGHAM (UAB)

Open-Rank Professor Position – Condensed Matter Physics

The UAB Department of Physics, https://www.uab.edu/cas/physics/, invites applications for an Open Rank, open tenure, faculty position that will strengthen the Department's program in **Theoretical or Experimental Condensed Matter Physics**. Research areas of interest include, but are not limited to, the physics of quantum & biological materials using ultrafast spectroscopies, extreme pressure and electromagnetic fields, or quantum/data-driven computing. The new faculty member must have an outstanding publication record and strong commitment to excellence in teaching and supervising research at both graduate and undergraduate levels. The rank will be commensurate with the applicant's track record. We particularly welcome applicants from groups underrepresented in physical sciences. Screening of applications will begin immediately and continue until the position is filled. Full consideration will be given to all applications received by January 5, 2020, that include: (i) short letter explaining the applicant's research, extramural funding ideas, and qualifications relevant to this position; (ii) full curriculum vitae; (iii) statement on planned and past research projects; (iv) statement on teaching and mentoring; (v) three reference letters. All applications will be handled through **http://uab.peopleadmin.com/postings/5502**. For more information, please contact the search committee chair, Prof. Yogesh Vohra, at **ykvohra@uab.edu**.

The University of Alabama at Birmingham is a comprehensive urban university, with the nation's third-largest public hospital, that rapidly evolved into a world-renowned research university and health care center. Times Higher Education ranked UAB #1 young U.S. university for two years in a row, top 12 worldwide. With over 22,000 students and a campus covering more than 100 city blocks, UAB is focused on the future of research, teaching, health care, and community service. We are also a founding partner of Innovation Depot, the largest high-tech incubator in the southeast. Our research-driven, student-centric Physics Department currently has 20 faculty and instructors. It has experienced recent growth by focusing on (i) Modeling & Simulation using high-performance, data-driven & quantum computing, (ii) Advanced Materials properties under extreme environments and stimuli, (iii) Photonics & Lasers, and (iv) Technology-Enabled Physics Education.

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Larry Fishbein, Publisher

NEW PRODUCTS

Focus on lasers, imaging, and microscopy

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 the product description. For all new products submissions, please send to ptpub@aip.org.

Andreas Mandelis

Motorized XY stage

Physik Instrumente (PI) has introduced a motorized XY stage optimized for optical microscopy. The M-971 is designed to be integrated with systems used for inspection, lithography, and biomedical engineering. According to the company, the stage's components make it suitable for cost-sensitive OEM applications. The drivetrain is based on a widely used PI linear stage with proven reliability and long lifetime. Several short crossed-roller guides distribute the load evenly over a large surface and ensure high stiffness and good travel accuracy. Since a simple controller can be used with the M-971's stepper motors, encoders are not needed. The XY stage is equipped with limit and reference switches to ensure fast, precise referencing and safe operation. ***Physik Instrumente LP***, *16 Albert St, Auburn, MA 01501, www.pi-usa.us*

UV-enhanced cameras

PCO has enhanced its cameras for microscopy and life sciences. It has added a specialized input window inside its pco.panda 4.2 bi UV and pco.edge 4.2 bi UV to help users achieve high quantum efficiency in the UV-wavelength range. The systems are based on the company's scientific CMOS cameras with advanced back-illuminated sensor technology. That technology makes the compact pco.panda 4.2 bi UV suitable for demanding lighting conditions, even without active cooling. The pco.edge 4.2 bi UV has an adjustable cooling system that allows the use of air or water to cool the sensor down to −25 °C. At that temperature, the dark current is reduced to 0.2 e^-/pixel/s. The cameras' high resolution and 6.5 × 6.5 μm^2 pixel size ensure detail diversity and high-quality images. ***PCO-Tech***, *6930 Metroplex Dr, Romulus, MI 48174, www.pco-tech.com*

Single-frequency green laser

M Squared has made available a single-frequency, 532 nm laser for use in demanding scientific and industrial applications such as quantum research and systems, integrated circuits, space, and biophotonics. Equinox can operate as a stand-alone laser and is suitable as a pump source for CW and pulsed titanium:sapphire laser systems. It can also be used for pumping dye lasers, frequency doubling and mixing, and optical tweezing and trapping. Equinox features up to 18 W output, consistent low-noise performance at all powers, and narrow line width. It offers high mechanical and thermal stability, and Invar materials minimize effects from vibrations and thermal variations. According to the company, the fully automated laser is reliable, robust, and easy to use. ***M Squared***, *1 Kelvin Campus, West of Scotland Science Park, Glasgow G20 0SP, UK, www.m2lasers.com*

Flexible laser-wavelength selector

Spectrolight has brought to market the flexible wavelength selector (FWS) Poly laser version, a tunable filter that uses the company's TwinFilm technology and a USB connector to provide simple software control (scanning or setting) of the center wavelength and bandwidth. It is compatible with supercontinuum lasers from NKT Photonics, YSL Photonics, and Leukos, and it debuts with six models that cover the visible-, UV-, and custom-wavelength ranges. Depending on the model, the center-wavelength tuning range can be as wide as approximately 500 nm or as narrow as approximately 50 nm, and the bandwidth can be adjusted from around 3 nm to 15 nm. Applications for the FWS Poly include hyperspectral imaging, fluorescence microscopy, and machine vision; with OEM instruments, it can be used in life sciences instrumentation for flow cytometry and DNA sequencing. ***Spectrolight Inc***, *19800 MacArthur Blvd, Ste 300, Irvine, CA 92612, www.spectrolightinc.com*

Compact DPSS laser

Quantum Composers has added a diode-pumped solid-state (DPSS) neodymium-doped yttrium aluminum garnet laser to its Jewel laser series. The MiniJewel delivers 4 mJ of energy at its fundamental output of 1064 nm with repetition rates up to 50 Hz. The pulsed, conductively cooled, multimode laser comes with an optional built-in attenuator. It can be supplemented with nonlinear modules for 1064/532 nm, 532/355 nm, or 355/266 nm. The compact laser can be mounted on microscopes, integrated into portable systems, and used in limited-space applications. According to the company, the MiniJewel's rugged resonator design prevents misalignment more effectively than other lasers. Applications include laser-induced breakdown spectroscopy, particle image velocimetry, and microablation. ***Quantum Composers Inc***, *212 Discovery Dr, Bozeman, MT 59718, www.quantumcomposers.com*

Fluorescence multiple-source laser module

Fisba has expanded the features and functions of its READYBeam multiple-source laser module to offer users a simple, compact, powerful device for fluorescence excitation in analytical instruments and microscopy applications. According to the company, the updated instrument has an integrated laser driver that reduces the footprint, development time, and integration risk of multiple-wavelength light sources. The module features 405 nm, 488 nm, and 638 nm wavelengths and output power greater than 30 mW per wavelength. Its benefits include embedded cooling, photo feedback, and optica communication. The unit is available in two primary configurations: the READYBeam bio and READYBeam ind. ***Fisba AG***, *Rorschacherstrasse 268, 9016 St Gallen, Switzerland, www.fisba.com*

Near-IR phase modulator

Laser Components has made an addition to its NIR-MPX series of phase modulators from Photline Technologies. The devices are designed to operate in the 1000 nm wavelength band and are available with various modulation bandwidths, from low frequency to 10 GHz and beyond. They use a proton-exchanged-based waveguide process that delivers high stability and a high photorefractive threshold. The latest addition to the series, the 2 GHz NIR-MPX-LN-02 model, offers a bandwidth and half-wave voltage combination that makes it suitable for spectral broadening applications. ***Laser Components USA Inc***, *116 S River Rd, Bldg C, Bedford, NH 03110, www.lasercomponents.com*

Standard and high-performance cameras

The new ace 2 camera series from Basler includes two product lines: the economical ace 2 Basic, for standard vision-system applications, and the ace 2 Pro, for more demanding requirements. Both lines feature state-of-the-art CMOS sensor technology and GigE or USB 3.0 interfaces. The Basic models offer 2.3 MP resolution and 51 fps with the GigE interface and 160 fps with the USB 3.0 interface. The ace 2 Pro line offers two advanced in-camera features. Compression Beyond compresses image data directly in the camera's field-programmable gate arrays in real time without sacrificing image quality, and it makes more bandwidth available, which ensures higher frame rates. Pixel Beyond uses an interpolation method developed by Basler to change the pixel size and thereby allow adjustments of sensor characteristics, so resolution can be scaled and the amount of data reduced. ***Basler Inc***, *855 Springdale Dr, Ste 203, Exton, PA 19341, www.baslerweb.com*

Ytterbium fiber-based laser

Chromacity has made a 520 nm addition to its family of air-cooled ytterbium fiber-based lasers. Essentially a frequency-doubled version of the company's 1040 nm laser, it provides a fixed 520 nm output at a power range from 500 mW to 1 W and the option to deliver dual output at 520 nm or 1040 nm from a single unit. The Chromacity 520 is suitable for use in life and materials sciences, fundamental research, nanoparticle technology development, photodynamic therapy, and multiphoton imaging. According to the company, the laser's ultrashort pulse durations and high peak powers may help generate new developments in optical parametric oscillator pumping, four-wave mixing, amplifier seeding, terahertz generation, and other nonlinear processes. ***Chromacity Ltd***, *Livingstone House, 43 Discovery Ter, Research Ave N, Riccarton, Edinburgh EH14 4AP, UK, www.chromacitylasers.com*

Long-focal-length collimators

HGH has expanded its IRCOL range of collimators by adding a 4 m focal length designed to characterize and validate the performance of very powerful IR- and visible-range cameras. The company claims that the long length allows the new IRCOL 300-4000 to stimulate very high frequencies for the highest-resolution testing. Driven by HGH's Infratest software, the IRCOL 300-4000 can perform tests to determine noise-equivalent irradiance, spatial resolution, modulation transfer function, distortion, noise-equivalent temperature difference, and minimum resolvable temperature difference. ***HGH Systèmes Infrarouges***, *10 Rue Maryse Bastié, 91430 Igny, France, www.hgh-infrared.com*

Objective positioner

According to Prior Scientific, its NanoScan OP400 piezo-based objective positioner provides repeatable Z-stacking and the fastest step-and-settle time of any similar device. Its innovative mechanical design and integral capacitive feedback sensors deliver high positioning accuracy and resolution. The OP400 is compatible with most microscopes and objective lenses and has a range of optimized settings for different objective sizes, weights, and performance requirements. Coupled with the NPC-D-6110 digital controller from Prior's Queensgate Instruments brand, the system is quick to set up and use. With variable acceleration and deceleration algorithms, the digital-control technology can precisely manage stage movement. ***Prior Scientific Instruments Ltd***, *3-4 Fielding Industrial Estate, Wilbraham Rd, Fulbourn, Cambridge CB21 5ET, UK, www.prior.com* PT

Northwestern University

The **Department of Materials Science and Engineering** at Northwestern University seeks outstanding applicants for two full-time tenure-track faculty positions at the Assistant Professor level. We are interested in candidates with experimental, computational, or theoretical expertise in any aspect of materials science and engineering. We are dedicated to building a diverse community and encourage applications from underrepresented groups. The university recognizes that attracting world-class faculty may require addressing dual-career needs and has in place policies to promote work-life balance. The MSE department will also work alongside the university in securing employment eligibility for international applicants.

Review of applications will begin **December 1, 2019** and continue until positions are filled. Recruited applicants are anticipated to commence their position in Fall 2020, with a later start date possible. Applications must be submitted online at https://www.mccormick.northwestern.edu/materials-science/careers/ and include a cover letter, curriculum vitae, research statement, teaching statement, and contact information for 3-5 references. Northwestern University is an Equal Opportunity, Affirmative Action Employer of all protected classes, including veterans and individuals with disabilities. Women, racial and ethnic minorities, individuals with disabilities, and veterans are encouraged to apply. Hiring is contingent upon eligibility to work in the United States.

Max Planck Institute for Chemical Physics of Solids

Max Planck Institute for the Physics of Complex Systems

MAX-PLANCK-INSTITUT FÜR CHEMISCHE PHYSIK FESTER STOFFE

mpipks

The Physics of Quantum Matter Division of the Max Planck Institute for Chemical Physics of Solids and the Division of Condensed Matter of the Max Planck Institute for the Physics of Complex Systems seek candidates for the joint position of a

Research Group Leader in Theoretical Condensed Matter Physics

Candidates are expected to build and lead a group to pursue a high-quality research program. They should have a strong postdoctoral research track record in theoretical condensed matter and/or materials physics. The group is a joint group of the two institutes, and is hence encouraged to interact strongly with colleagues specialising both in theory and in experiment.

The position has a flexible starting date in 2020, and is for a five-year period with the possibility of renewal. Remuneration is competitive (TVöD 15) and generous funds are available for hiring post-docs and PhD students.

Please send your CV, publication list and a description of research accomplishments and future plans to schuppe@pks.mpg.de (mentioning 'JRG20', preferably a single pdf file via e-mail), and arrange for three letters of reference to be sent. Any questions may be addressed to the directors of the divisions involved (Professor Andrew Mackenzie at MPI-CPfS or Professor Roderich Moessner at MPI-PKS).

We especially encourage women to apply. Consideration of applications will start immediately until the position is filled; for primary consideration please submit all materials by **8 January 2020**.

The Max Planck Society is committed to employing more individuals with disabilities, who in the case of equal qualifications will take precedence.

MAX-PLANCK-GESELLSCHAFT

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Tenure-Track Faculty Position

The Department of Physics invites applications for tenure-track faculty positions at the Assistant Professor level. Ranks at Associate Professor or above will also be considered for candidates with exceptional record of research excellence and academic leadership. Applicants must possess a PhD degree in physics or related fields and have evidence of strong research productivity.

We seek strong experimental candidates in hard condensed matter physics (including quantum materials and low dimensional materials, materials with strong electronic correlations and novel wave functional materials). Candidates with outstanding record in experimental atomic, molecular and optical (AMO) physics are also encouraged to apply.

Appointee is expected to assume teaching responsibilities for undergraduate and graduate courses, and to conduct vigorous research programs. Further information about the Department is available at http://physics.ust.hk

Starting salary will be commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. Initial appointment will normally be on a three-year contract. A gratuity will be payable upon successful completion of contract.

Application Procedure:

Applicants should submit their curriculum vitae, together with a cover letter, a complete list of publications, a brief research statement and a teaching statement, and three reference letters, via AcademicJobsOnline.Org at (https://academicjobsonline.org/ajo/jobs/6695)

Please quote reference number "PHYS2509" in your application materials.

Screening of applications will begin immediately, and will continue until the position is filled.

PROFESSOR NANOFABRICATION
(AP 18-07)

Institut national de la recherche scientifique (tenure-track position)

Context and summary

The Institut national de la recherche scientifique (INRS) is the only academic institution in Québec (Canada) dedicated exclusively to research and training at the graduate level. The influence of our faculty, researchers, and students extends worldwide. In partnership with the scientific community and the private sector, we are proud to contribute to societal development through our discoveries and through the training of young scientists.

INRS – Énergie Matériaux Télécommunications (EMT) Research Centre would like to hire a new faculty in the area of **Micro- and Nanofabrication**. The successful candidate will collaborate with multidisciplinary research teams at the INRS Énergie Matériaux Télécommunications Research Centre in the areas of (but not limited to) electron-beam lithography, nanometer pattern transfer including plasma etching techniques, and fabrication and characterization of micro- and nanosystems e.g. for applications in photonics, optoelectronics, energy conversion and storage, solid state lighting, chemical and environmental sensing, biosensing and biomedical engineering.

The Centre hosts the unique major research Infrastructure of Nanostructures and Femtoscience (http://lmn.emt.inrs.ca/EN/inf.htm), which comprises the Advanced Laser Light Source, the Laboratory of Micro and Nanofabrication, and the Infrastructure for Advanced Imaging. The new faculty will work in an environment where about forty professors-researchers undertake leading-edge research and training in diverse areas of sustainable energy, advanced materials, ultrafast photonics, telecommunication systems and nanobiotechnology.

Main duties and responsibilities

- Develop an original and innovative program.
- Secure external funding from a variety of funding agencies, both provincial and federal, also involving various partners from the public and private sectors whenever needed/pertinent. Potential sources of funding include the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds québécois de la recherche sur la nature et les technologies (FQRNT).
- The candidate is expected to establish collaborations with research teams already in place, while developing or maintaining partnerships with groups outside the EMT research center. The ability to develop partnerships with the private sector is particularly valuable.
- Participate in teaching and training at the graduate level (both M.Sc. and Ph.D. students), as well as supervising post-doctoral fellows and research personnel.

Requirements

- A doctoral degree in a relevant discipline (physics, materials science, engineering, chemistry).
- An outstanding record of research accomplishments that will enable her/him to successfully develop a strong independent research program.
- The aptitude for teaching and supervising graduate students and other trainees.
- The ability to work in a multidisciplinary team and within research networks.
- The ability to collaborate with industrial partners.

Working language

French is the official language at INRS. Fluency in English is required. Candidates whose native language is not French are encouraged to apply. The Centre will provide them with all the resources necessary to facilitate their learning of the French language.

Workplace

Institut national de la recherche scientifique (INRS)
Centre Énergie Matériaux Télécommunications
1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA
Varennes is located on the South Shore of Montreal.

Salary

Salary and benefits are in accordance with the current collective agreement at INRS.

How to apply

Interested applicants should send their application including a complete curriculum vitae, a copy of their three most significant publications, a three page summary of their research interests, a statement of teaching experience and philosophy, and the names and contact information of three referees, before **January 24th 2020** indicating position number AP 18-07 by e-mail at **concours@emt.inrs.ca** or by mail to:

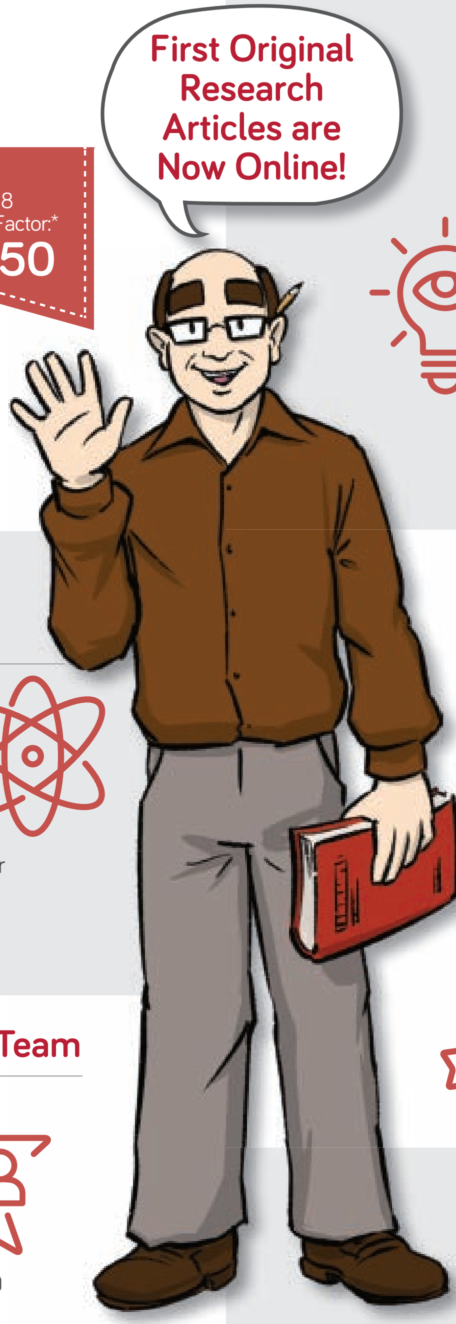
Director
Institut national de la recherche scientifique (INRS)
Centre Énergie Matériaux Télécommunications
1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA

INRS
Institut national de la recherche scientifique

INRS subscribes to an equal access employment program and an equity employment program. The Institute invites women, visible minorities, ethnic minorities, natives and people with disabilities to apply. Priority will be given to candidates with Canadian citizenship or permanent resident.

Applied Physics Reviews

5 FACTS ABOUT APR



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With an IF of **12.750***, APR is an ideal journal for articles on important topics in experimental or theoretical research in applied physics or applications of physics to other branches of science.

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Historically a review journal, APR began considering submissions of original research for publication in January 2019. Articles report on important and novel research studies of general interest to the applied physics community.

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Luigi (pictured) is real! He is one of several Ph.D. scientists on our Editorial Team. They each have active experience in reviewing and publishing papers and their combined experience provides the foundation for the premium service and attention your research will receive. Read about Luigi and the rest of the team on our website **products.aip.org/apr**

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PHYSICS TODAY PRODUCT PICKS

Mitchell Jay Feigenbaum

Mitchell Jay Feigenbaum, a theoretical physicist whose inquiring mind and intense focus enabled him to contribute broadly across many fields, died of a heart attack on 30 June 2019 in New York City. Mitchell's most celebrated work was his discovery of the universality of the period-doubling transition to chaos and the associated Feigenbaum constant, $\delta = 4.6692016\ldots$. His predictions were confirmed experimentally in Albert Libchaber's convection experiments in 1979. For their work, the two men shared the 1986 Wolf Prize in Physics.

Born in Philadelphia on 19 December 1944, Mitchell graduated in 1964 at age 19 from City College of New York with a degree in electrical engineering. He entered MIT that same year but switched to physics. He received his PhD in 1970 with a thesis on particle physics under the supervision of Francis Low. A postdoctoral fellowship at Cornell University proved crucial to his career, as he was introduced to the renormalization group ideas of Kenneth Wilson and met Peter Carruthers. Following another postdoc at Virginia Tech, he was hired by Carruthers in 1974 to the rejuvenated theoretical division at Los Alamos National Laboratory. He moved to a professorship at Cornell in 1982 and to his final position at the Rockefeller University in 1986. In 1984 he was awarded a MacArthur Fellowship.

Mitchell was a true intellectual, reminiscent of the 18th-century natural philosophers, who considered everything in nature their purview and did science before the word "scientist" was even invented. Mitchell worked only on problems that excited him and insisted on understanding everything from first principles and on his own terms. He was also capable of ferocious concentration: During his study of period doubling, he often worked 48 hours at a stretch to keep everything in his mind.

Although Mitchell was extremely proficient with computing, and with computer algorithms in particular, he was skeptical of the computer's ability to reveal dramatic new insights unless one had what he called a "conceptual schema" to interpret the results. He once remarked, "It is hard to learn by seeing. So why should the scales miraculously fall off when one stares at a computer screen?" Indeed, Mitchell's discovery of universality arose because he was using an HP-65 calculator. Its slowness compelled him to examine carefully the parameter values of successive period doublings, and he recognized that they converged geometrically at the rate δ.

Mitchell's broad interests and remarkable depth enabled him to contribute significantly to fields beyond physics. He made transformative contributions to cartography by inventing optimal conformal projections, which minimize distortions in shapes and relative areas of objects in planar maps of Earth's surface. Further, he created a chaotic dithering program for efficient map labeling for maximum legibility and aesthetic appeal. Those inventions were at the heart of the innovative third edition of the Hammond World Atlas, published in 1992, which is truly a work of art.

In the 1990s, while serving on the National Research Council's Committee on Next-Generation Currency Design, charged with suggesting ways to deter counterfeiting, Mitchell used his unusual insights into numbers to devise patterns that cannot be reproduced by even high-resolution digital copiers; the copiers will introduce new visible features in the copy. That work is reminiscent of Isaac Newton's proposal to introduce milled edges in coins to prevent clipping.

His interest in computer algorithms led Mitchell in 1996 to cofound Numerix, a company that develops novel software algorithms to improve the speed and accuracy of calculations used to price financial derivatives.

Mitchell's most recent studies were on visual perception. His goal was to infer "rules" associated with vision and perception by using carefully crafted applications of optics, supplemented by visual neurophysiology. A major work of his in that area remains unpublished, but we hope it will soon be available to the world.

Although Mitchell eschewed administrative responsibilities, he lent his ideas and prominence to important ventures, including the founding of the Center for Nonlinear Studies at Los Alamos, the creation of the US–USSR Chaos/XAOC conferences, and the formation of the journal *Chaos* (published by the American Institute of Physics, which also publishes PHYSICS TODAY). In the mid 1990s, with Rockefeller's then president Torsten Wiesel, Mitchell founded the university's Center for Studies in Physics and Biology, which anticipated efforts elsewhere to inject modern mathematics and physics into biology.

PREDRAG CVITANOVIĆ

Mitchell Jay Feigenbaum

Mitchell was a unique individual who, in the words of the poet William Blake, was able "To see a World in a Grain of Sand, And a Heaven in a Wild Flower." Mitchell discussed extensively the intricacies of the music of Schubert, Beethoven, and Wagner; the art of Rembrandt and Picasso; the philosophy of Kant and Schopenhauer; and the psychoanalysis of Freud. Indeed, Blake's famous portrait of Newton taking the measure of the world with a compass provides an appropriate image to remember our remarkable colleague.

We are grateful to Mitchell's many friends and colleagues for sharing with us their reminiscences of him.

David Campbell
Boston University
Boston, Massachusetts

Gemunu Gunaratne
University of Houston
Houston, Texas

Eric Siggia
Rockefeller University
New York City

Jerry Paul Gollub

Jerry Paul Gollub was a remarkably creative physicist who conducted foundational experiments in nonlinear dynamics, including the first observation and characterization of the transition from order to chaos in fluid systems. His work contributed greatly to the understanding of complex dynamical behavior. His lucid papers and lectures made him widely sought as a lecturer at universities and international conferences.

Jerry was born in Saint Louis, Missouri, on 9 September 1944 and died in Haverford, Pennsylvania, on 8 June 2019. He graduated with an AB degree from Oberlin College in 1966 and with a PhD from Harvard University in 1971; his thesis adviser was Michael Tinkham. His primary appointment during the entirety of his professional career, from 1971 to 2012, was at Haverford College. In 1997 he was named the John and Barbara Bush Professor of Natural Sciences. His steadfast commitment to undergraduate education and to Haverford led him to decline offers of professorships at several major research universities.

In his Haverford laboratory, Jerry mentored more than 100 undergraduates and worked with postdocs and with graduate students from the University of Pennsylvania, where he was an adjunct professor. Because of the world-class research he conducted, in 1986 he became the first recipient of the American Physical Society (APS) Prize for a Faculty Member for Research in an Undergraduate Institution. He also held visiting appointments at the University of Paris VII in 1985, École Normale Supérieure in 1991, and the Weizmann Institute of Science in 1997–98.

My fondest memories of Jerry are from the period 1974–75, when we collaborated on experiments designed to test Lev Landau's 1944 prediction that the transition to turbulence would occur through an infinite sequence of instabilities, each adding a new frequency to the motion, as the Reynolds number was increased. In our intense collaboration, Jerry and I developed a deep friendship and a research style and purpose that we sustained throughout our careers.

LISA J. GODFREY/HAVERFORD COLLEGE

Jerry Paul Gollub

Our experiments, conducted at the City College of New York, yielded time series of the fluid velocity measured at a point between concentric cylinders. As the inner cylinder rotation rate (proportional to the Reynolds number) was increased, power spectra of the velocity time series revealed a transition from time-independent flow to a state characterized by a single frequency, in accord with the Landau picture. At a higher Reynolds number, a second frequency component, incommensurate with the first, appeared in the power spectrum, just as Landau had anticipated. With further increase in the Reynolds number, however, the spectra contained increasing broadband noise but no additional discrete frequency components. The noisy behavior differed from the expected Landau scenario, but the observation was consistent with models and analyses of chaos developed in the 1960s and 1970s.

In the 1980s Jerry and his group at Haverford developed a technique for visualizing spatial patterns in convecting fluids. With it, they investigated how competition between different spatiotemporal modes led to chaos. In the late 1980s, Jerry used particle-tracking methods to characterize chaotic mixing in time-periodic convective flows, the formation of fractal and dendritic structures in solidification processes, and pattern formation and chaos in surface waves. He also conducted a series of imaginative experiments on the dynamics of granular materials. In 2008–9 Jerry was a Leverhulme Visiting Professor at Cambridge University, where he collaborated with Raymond Goldstein, who had developed green algae as model organisms for biological fluid dynamics. Their experiments revealed diffusive yet non-Gaussian tracer statistics in suspensions of swimming microorganisms.

From 2000 to 2002, Jerry served as cochair of the National Research Council committee that produced the study *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools*. In 2005–8 he served on the National Academy of Sciences governing council.

Jerry was awarded the 2003 APS Fluid Dynamics Prize "for his elucidation of chaos, instabilities, mixing and pattern formation." He also served for three decades in many APS elected and appointed positions, including on the council and the executive board.

Jerry is greatly missed by his many friends, students, postdocs, and other collaborators throughout the world. His innovative experiments on the complex dynamics of systems driven away from thermodynamic equilibrium will have lasting influence. He will also be remembered as a tireless advocate for high school and undergraduate science education, especially in physics, and for his contributions to the general good of the broad scientific community.

Harry L. Swinney
Austin, Texas PT

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John J. Quinn
25 September 1933 – 8 October 2018

Rod Linn leads development, implementation, testing, and application of computational models of wildfire behavior in the Earth and environmental sciences division at Los Alamos National Laboratory in New Mexico.

Fluid dynamics of wildfires

Rodman Linn

Once a wildfire is ignited, complex interactions with the local winds affect how it behaves.

Wildland fires are an unavoidable and essential feature of the natural environment. They're also increasingly dangerous as communities continue to spread away from urban areas. Unfortunately, a century of wildfire exclusion—the strategy of putting out fires as fast as they start—has led to a significant buildup of fuel in the form of overgrown forests. Continuing to keep wildfires at bay is simply not sustainable. In 2018, nearly 60 000 fires scorched parts of the continental US. California wildfires exemplify what can happen when they burn through communities: In November alone that year fires killed more than 90 people and destroyed some 14 000 homes and businesses.

Decision makers are striving to find ways to manage the consequences of those fires and yet still allow them to thin out dense, fuel-heavy forests and reset ecosystems. Among other things, the goal requires that land managers be able to predict the behavior of wildland fires and their sensitivity to ever-changing conditions. Many factors, including the interactions between fire, surrounding winds, vegetation, and terrain, complicate those predictions.

That ambient winds influence fire behavior is well known. Less understood is how fire influences the winds and how the feedback affects the fire's evolution. As the fire rages, it releases energy and heats the air. The rising air draws in air below it to fill the gap in much the same way as air is drawn into a fireplace and rises up a chimney. The interaction between rising air and ambient winds controls the rate at which surrounding vegetation heats up and whether it ignites. The interaction thus determines how quickly a fire spreads.

Fuel matters

The influence of the fire–atmosphere coupling is much greater in wildland fires than in building fires. Wildland fires are fed by fine fuels—typically grasses, needles, leaves, and twigs; often, tree trunks and large branches do not even burn. Buildings burn thicker fuels, such as boards, furniture, and stacks of books. The difference matters because fine fuels exchange energy more efficiently with surrounding hot air and gases. In those hot, fast-moving gases, the fuels' temperature rises quickly to the point where they ignite.

But the converse is also true. Because wildland fuels are primarily fine, they are also efficiently cooled when the surrounding ambient air is cooler than they are. That means that the indraft of air caused by a fire may actually impede its spread. A rising plume can draw cool air over foliage and litter near a fire line and prevent those fine fuels from heating. The grasses just outside a campfire ring are a case in point: They are continuously exposed to the fire's radiant heat, but the cool indraft effectively prevents them from reaching the point of ignition.

The spread of a wildfire is sometimes conceptualized as an advancing wall of flame that the wind forces to lean toward unburned fuels that then ignite in front of the fire. Although that wall-of-flame paradigm simplifies models of fire behavior, it is not correct. Convective cooling would prevent the wall of flame from spreading by radiation alone, and for convective heating to spread the fire, the wind would have to be strong enough to lean the flame to the point where it touches the unburned fuel. Were that true, the fires would be unable to spread in low-wind conditions because the buoyancy-driven updrafts would keep the flames too upright.

If you were to look upon an advancing wildfire from the front, you would actually see a series of strong updrafts, visible as towers of flame that are separated by gaps, as shown in figures 1 and 2. The towers are regions where the buoyancy-driven updrafts carry heat upward. They are fed by ambient wind drawn into the gaps between them, as described earlier. When the ambient wind is strong enough, it pushes air through the gaps between the towers, but that air is heated as it blows over burning vege-

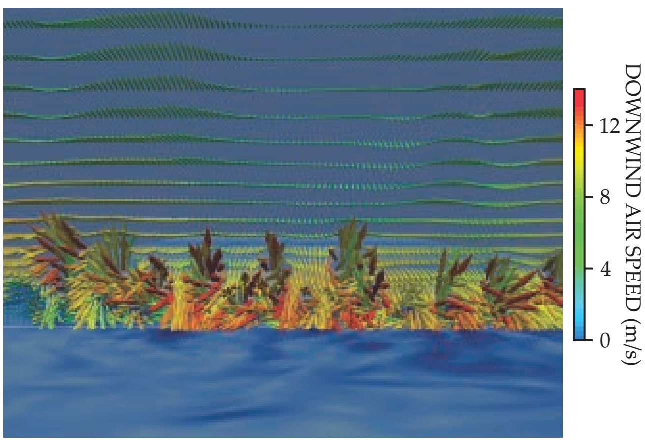

FIGURE 1. TOWERS AND TROUGHS, IN SIMULATION. This computer-generated snapshot of a grass fire emerges from the page toward the reader and shows wind-speed vectors in the vertical plane in front of a wildfire. Updraft towers are evident where the vectors point upward. In the gaps between the towers, air rushes in and feeds unburned fuel in front of the fire. Red vectors signify wind currents that are 12 m/s or higher due to the acceleration of air produced by the fire's heat rising upward. As shown by the green vectors above the flames, the ambient wind is a breezy 6 m/s.

FIGURE 2. TOWERS AND TROUGHS, IN REALITY. In this experimental grass fire, the few visible peaks are separated by gaps in which the wind currents sweep downward between the flames and feed the peaks on opposite sides. (Courtesy of Mark Finney, US Forest Service, Missoula Fire Sciences Laboratory.)

tation. The motion of hot gases through the fire line disrupts the indraft of cool ambient air and ignites grasses and foliage in front of the fire. That's the primary way a wildfire spreads.

A second factor that influences the spread is the shape of the fire line, because different parts of the blaze compete for wind. The headfire, the portion moving the fastest, often has trailing flanking fires that form a horseshoe shape and open up to the ambient wind. Part of that wind gets redirected toward the flanks of the horseshoe. The strength, length, and proximity of the flanking fires to each other thus help determine how much wind reaches the headfire. The narrower the horseshoe is, the larger the fraction of wind diverted to the flanks, the lower the wind speed reaching the headfire, and the slower it spreads.

Another factor to be considered is the spatial arrangements of fuels. The potential for wildfires spreading from the crown of one tree to another is reduced when the spacing between trees increases. In that case more horizontal wind is required for flames to jump between trees. Indeed, removing trees is a common fire-risk-management practice. But the strategy behind it is more complex than just removing fuel. Gaps in a forest canopy also make it easier for high-speed winds above the canopy to reach fires on the ground. So although reducing the number of trees might reduce the crown-to-crown fire activity, it might increase the spread rate of a surface fire.

Prescribed fire

In some regions of the US, land managers counter the threat of wildfires and promote ecosystem sustainability by purposefully lighting fires. Carefully controlled, prescribed burns, which clear duff and deadwood on the forest floor, are often lit at multiple locations; fire-induced indrafts at one location influence fires at other locations. For example, a single line of fire under moderate winds might reach spread rates and intensities that are undesirable or uncontrollable, but the addition of another line of fire upwind can influence how much ambient wind reaches the original fire and thus reduces its intensity.

The spread of the upstream fire line, ignited second, is purposefully limited, as it converges on the area downwind where the first fire has burned off fuel. Practitioners can manipulate the flow of wind between fire lines by adjusting the spacing between ignitions. Fire managers might tie the various ignition lines together—reducing the fresh-air ventilation, increasing the interaction between the lines, and causing fire lines to rapidly pull together—to give themselves more control over the spread.

The interaction between multiple fire lines can even stop a wildfire in its tracks. When firefighters place a new fire line downwind of a fire, they often hope that the indrafts will pull the so-called "counter fire" toward the wildfire and remove fuel in front of it. Unfortunately, the maneuver requires a good understanding of the wildfire's indraft strength. Too weak an indraft could turn the counter fire into a second wildfire.

After realizing the huge significance of the wind interactions in wildfires over the past two decades, the science community is striving to better account for them. Those efforts should improve predictions of how a wildfire will behave in various conditions. To that end, some researchers, including me, use computer models to explicitly account for the motion of the atmosphere, wildfire processes, and the two-way feedbacks between them. Others perform experiments at scales ranging from meters (such as in wind tunnels) to kilometers (such as in high-intensity fires on rugged topography) for new insight on the nature of those fire–atmosphere interactions or to confirm existing models.

Additional resources

▶ J. M. Canfield et al., "A numerical investigation of the interplay between fireline length, geometry, and rate of spread," *Agric. Forest Meteorol*. **189**, 48 (2014).

▶ R. R. Linn et al., "Modeling wind fields and fire propagation following bark beetle outbreaks in spatially heterogeneous pinyon-juniper woodland fuel complexes," *Agric. Forest Meteorol*. **173**, 139 (2013).

▶ F. Pimont, J.-L. Dupuy, R. R. Linn, "Coupled slope and wind effects on fire spread with influences of fire size: A numerical study using FIRETEC," *Int. J. Wildland Fire* **21**, 828 (2012).

▶ J.-L. Dupuy et al., "Exploring three-dimensional coupled fire–atmosphere interactions downwind of wind-driven surface fires and their influence on backfires using the HIGRAD-FIRETEC model," *Int. J. Wildland Fire* **20**, 734 (2011).

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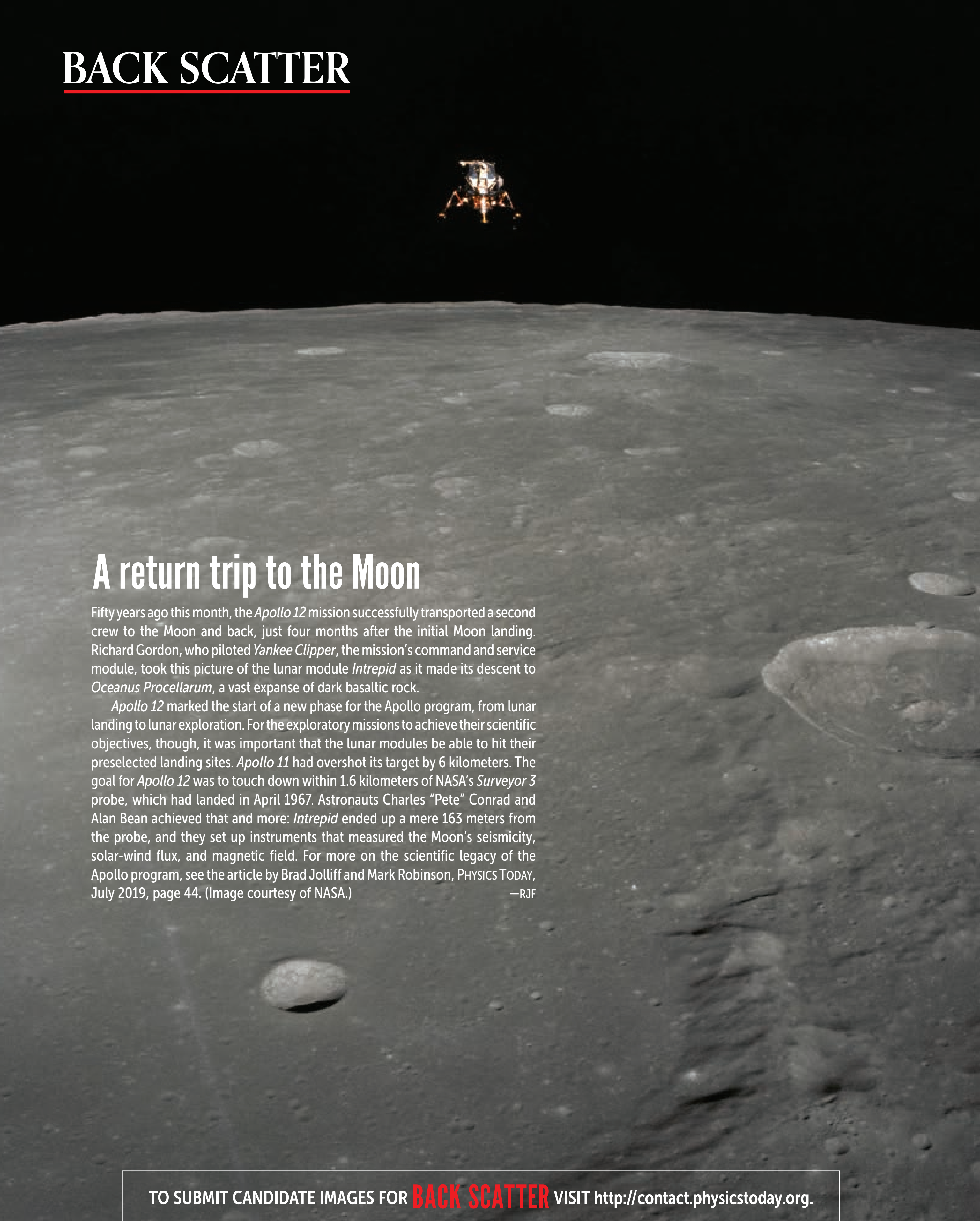
BACK SCATTER



A return trip to the Moon

Fifty years ago this month, the *Apollo 12* mission successfully transported a second crew to the Moon and back, just four months after the initial Moon landing. Richard Gordon, who piloted *Yankee Clipper*, the mission's command and service module, took this picture of the lunar module *Intrepid* as it made its descent to *Oceanus Procellarum*, a vast expanse of dark basaltic rock.

Apollo 12 marked the start of a new phase for the Apollo program, from lunar landing to lunar exploration. For the exploratory missions to achieve their scientific objectives, though, it was important that the lunar modules be able to hit their preselected landing sites. *Apollo 11* had overshot its target by 6 kilometers. The goal for *Apollo 12* was to touch down within 1.6 kilometers of NASA's *Surveyor 3* probe, which had landed in April 1967. Astronauts Charles "Pete" Conrad and Alan Bean achieved that and more: *Intrepid* ended up a mere 163 meters from the probe, and they set up instruments that measured the Moon's seismicity, solar-wind flux, and magnetic field. For more on the scientific legacy of the Apollo program, see the article by Brad Jolliff and Mark Robinson, PHYSICS TODAY, July 2019, page 44. (Image courtesy of NASA.) —RJF

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