PHYSICS TODAY
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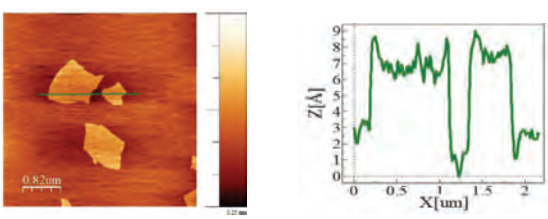
How wind makes *waves*

Cooling protons with lasers

Philosophy of thermodynamics

Doing science sustainably


NanoMagnetics
Instruments
ezAFM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PHYSICS TODAY

November 2021 | volume 74 number 11

FEATURES

ON THE COVER: Waves are born at the interface of air and water, where the flow is generally turbulent over a broad range of spatial and temporal scales. Scientists have been struggling with that complexity for more than a century. For a review of historical approaches and recent experimental and numerical efforts to resolve how momentum is transferred from winds to waves, turn to the article by Nick Pizzo, Luc Deike, and Alex Ayet on **page 38**. (Image by iStock.com/Anna_Om.)

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College after COVID-19

New surveys of undergraduate physics students reveal the impacts of the pandemic on education and offer insights into how departments can improve. Many students report learning less from remote instruction than they would have in person and limited access to study groups with peers.

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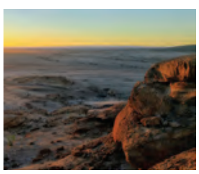

SARAH WILD

Shielded by quartz

Amid the unrelenting heat and aridity in the Namib Desert in southwest Africa, hardy bacteria manage to survive on the undersides of quartz stones. New interdisciplinary research reveals how the quartz shelters, by filtering out UV light, enable the bacteria to survive as they wait for water.

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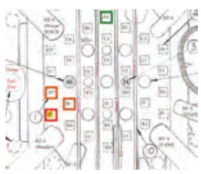

NIST

NIST reactor

On page 26 of the October issue, David Kramer recounted physicists' dismay with the indefinite shutdown of NIST's research reactor in Maryland. A new report details the operator errors, which the agency partly attributes to staff turnover, that led to a release of radiation in February.

physicstoday.org/Nov2021c

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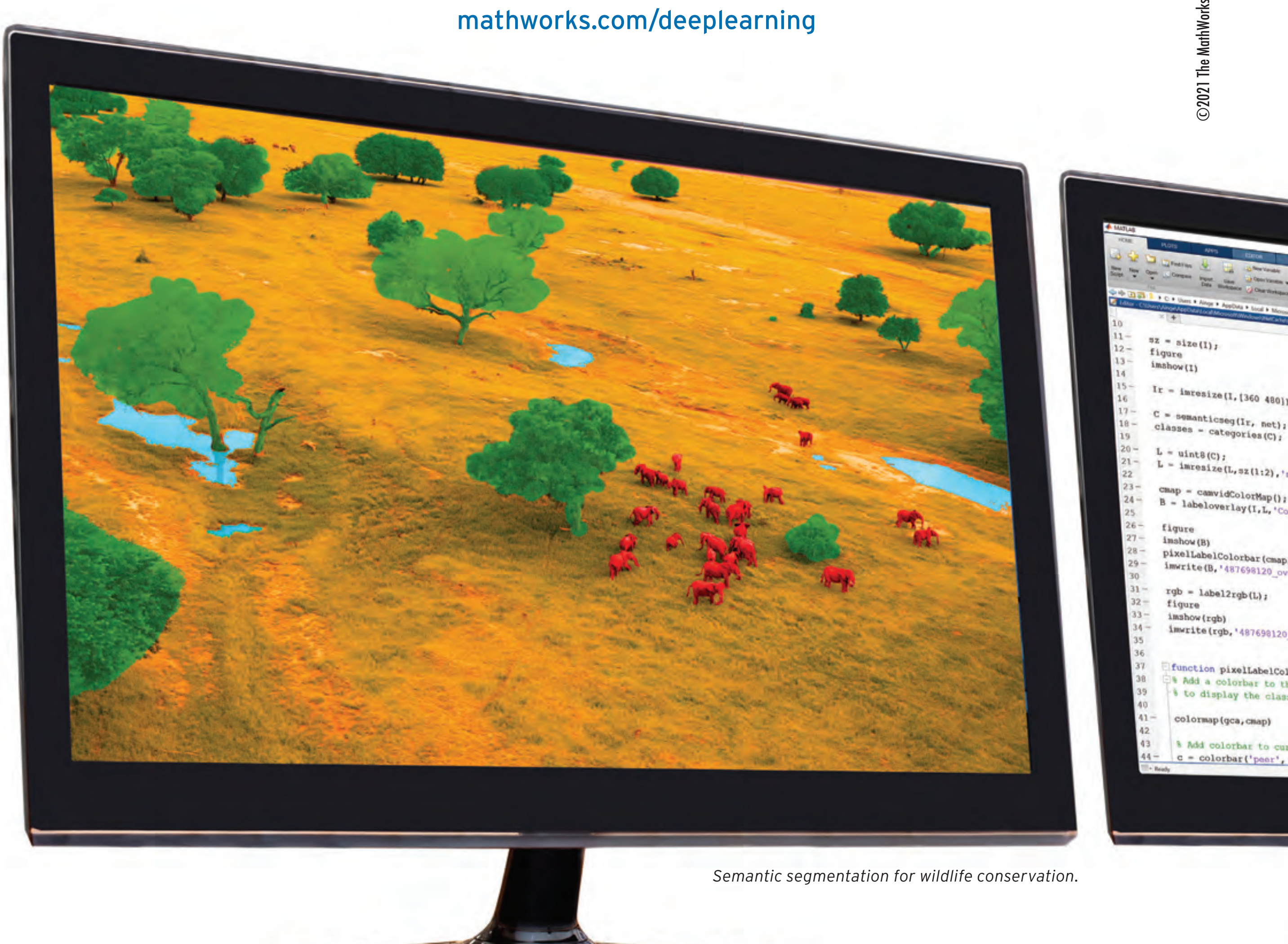
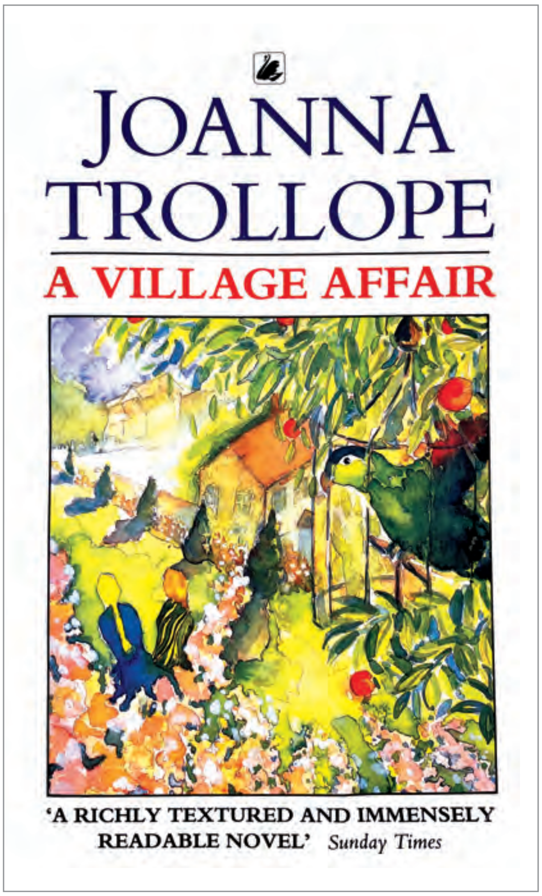


Aga sagas

Charles Day

Martin Amis, a former bad boy of British literature, was interviewed last year by the *New York Times* about his reading habits. Asked which genres he enjoys and which he avoids, he replied, "I confess I have never read an Aga saga or a bodice ripper—or indeed a western (though Hitler, incidentally, read nothing else)."

What, you might ask, is an Aga saga? The term was coined in 1992 to describe the novels of Joanna Trollope, which, being set amid middle-class society in the countryside of southern England, could be presumed to feature a type of stored-heat cooker called an AGA. By happenstance, my home library includes the epitome of Aga sagas, Trollope's *A Village Affair* (1989). Motivated to one-up Amis, I read the book. No AGAs appear within its pages, but thanks to YouTube, I spotted one in the trailer for the 1995 TV adaptation.



The acronym AGA stands for Aktiebolaget Svenska Gasaccumulator (Swedish Gas Accumulator Limited). The company has a connection with physics. Its chief engineer and inventor of the AGA cooker, Gustaf Dalén, was awarded the 1912 Nobel Prize in Physics "for his invention of automatic regulators for use in conjunction with gas accumulators for illuminating lighthouses and buoys."

Dalén was inspired to invent a cooker after being blinded in 1912 in an acetylene explosion. Spending more time at home, he noticed how much work his wife, Elma, put into fueling and running the family's stove. His solution was to create one that ran continuously. When introduced to the UK in 1929, the AGA stove became popular among the rich owners of large country houses.

AGAs not only serve as cookers, they also heat water. The stove is hot enough that it warms a kitchen. In a drafty old house, the kitchen is the coziest room because of the AGA.

But all is not well in Agashire. Since Trollope wrote her first Aga saga in the late 1980s, climate change has nudged up the mean temperature in the UK and led to more frequent and intense heat waves. AGAs run too hot for some parts of the country. Indeed, without much difficulty, I found a news story about a resident of Aldeburgh in the east of England who complained that her AGA made her kitchen "unbearably hot" during a 2019 heat wave. If the Aga saga endures, the genre's name will become vestigial.

A changed climate—invariably a worse one—has been a setting for science fiction for decades. Notable novels that feature warmer worlds include Octavia Butler's *Parable of the Sower* (1993), Peter F. Hamilton's *Mindstar Rising* (1993), Kim Stanley Robinson's *Forty Signs of Rain* (2004), and Sarah Hall's *The Carhullan Army* (2007).

Climate change is also showing up in literary fiction. In Iain Banks's *The Steep Approach to Garbadale* (2007), a gamekeeper on an estate in the Scottish Highlands laments, "Ah, it's all changing. We can see it here. The salmon and brown trout, they're mostly gone. And we don't get the winters we used to. I've got clothes and winter gear I just never wear—well, maybe a day a year or something—because it's milder all the time."

Banks himself became increasingly alarmed about climate change. In 2007 he sold his fleet of cars (BMW M5, Land Rover Discovery, Porsche 911 Turbo, and Porsche Boxter S) and replaced them with a Lexus RX 400 hybrid. PT

PURDUE UNIVERSITY

DEPARTMENT HEAD/PROFESSOR OF PHYSICS & ASTRONOMY

Purdue University seeks a new Head of the Department of Physics & Astronomy to lead a large and dynamic faculty towards its full potential for forefront scientific research, state-of-the-art teaching, and outstanding service to the community. Unprecedented enrollment increases and substantial growth in the campus combined with the nationally recognized quality of life of the surrounding community provide a strong foundation for a successful candidate to achieve an ambitious strategic vision.

Recent faculty initiatives provide a solid basis for growth, including a founding role in the DOE Quantum Science Center (at Oak Ridge), the preeminent Microsoft Quantum Lab Purdue for topological quantum computing, a key role in the NSF Harnessing the Data Revolution Institute (A3D3) for artificial intelligence, establishing a highly recognized new group in atomic, molecular & optical (AMO) physics, and ambitious projects in astrophysics spanning multi-messenger astronomy and utilizing the upcoming Vera Rubin Observatory and James Webb Space Telescope. Internationally recognized research in biophysics, condensed matter physics, high energy physics (including dark matter searches), and high energy nuclear physics is growing through the contribution of a young faculty, with one third of the 60-member faculty having joined since 2015 as new faculty continue to be recruited.

The Department of Physics & Astronomy is in the College of Science, which has spear-headed key initiatives in data & computational sciences and quantum science & engineering as well as recently making substantial investments in the geosciences, life sciences, environmental & atmospheric science, and space sciences & engineering.

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Applications should be submitted to:
https://career8.successfactors.com/sfcareer/jobreqcareer?jobId=16418&company=purdueuniv

Inquiries can be directed to Steve Durbin, chair of the head search committee (durbin@purdue.edu). Review of applications will begin after Jan 1, 2022 and will continue until the position is filled. A background check is required for employment at Purdue University.

Purdue University is an EEO/AA employer. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.

Rethinking the Nebra Sky Disk

The June 2020 issue of PHYSICS TODAY features an image of the Nebra Sky Disk as the illustration for a book review by Bernie Taylor (page 53). The sky disk is one of the earliest depictions of recognizable astronomical objects and relationships. Researchers have analyzed the disk extensively and debated about when it was created and where it was found. The disk had been used for generations, and elements were added to it over the years.[1]

The 30-centimeter disk originally featured elements that appear to be stars, the Sun or a full Moon, and a crescent Moon. Two golden arcs (one of which is now missing) were later added to the rim, which may have changed the disk's function. It has been posited that those arcs represent the distances the sunrise and sunset travel between solstices at the latitude where the disk was purportedly found in 1999 near Nebra, Germany.

Added later to the disk was another arc with two distinct lines along its length and many shorter ones radiating from its sides. Some have interpreted the object to be a mythical boat that ferries the Sun across the sky, with the short engraved strokes representing the oars.[2]

Images of the disk are often oriented so that the third arc is on the bottom, emphasizing the possibility that the symbol represents a boat. But if the two side pieces indeed represent the extent of sunrises and sunsets throughout the year, then the disk is meant to be viewed as though the edge represents the horizon, as with modern overhead sky charts. If that is the case, the disk's iconography might be interpreted differently.

The disk could be depicting the star cluster nearly midway between the side arcs—often thought to be the Pleiades—in the sky to the south, as it would sometimes appear from the area around Nebra. The object often thought to be a Sun boat then would be a fuzzy swath, low in the sky and to the north. I propose that it was intended as a representation of the aurora borealis, which would have made periodic appearances in Nebra. That would agree with the observational nature of the rest of the disk.


ANAGORIA/WIKIMEDIA COMMONS/CC BY 3.0
The Nebra Sky Disk

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2. "The Nebra Sky Disc (Germany)," nomination form for the International Memory of the World Register (2012), https://en.unesco.org/sites/default/files/germany_nebra_sky_disc.pdf.

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3-2-1 Contact: Scientists at the writers' table

Ingrid Ockert's article "S is for Science: The making of *3-2-1 Contact*" (PHYSICS TODAY, January 2021, page 26) ably portrays the pioneering roles viewer research and innovative programming played in the landmark series. But as a former curriculum developer at the Children's Television Workshop, which produced *3-2-1 Contact*, I'd like to point out that the article omits mention of a less obvious way in which the show broke new ground.

Rather than relying solely on outside content advisers, the Children's Television Workshop adopted the novel strategy of also bringing people with scientific expertise in-house to collaborate on the day-to-day making of *3-2-1 Contact*. After the show's maiden year, that responsibility fell to the biologist Ed Atkins, who went on to oversee all the science in the series. He was perhaps the first scientist invited into the intricacies of television production on this scale.

He was an inexhaustible source of ideas for episodes and a conduit for the many other scientists who contributed to the show in front of the camera or behind the scenes. In his work with writers, animators, editors, and producers, Atkins touched every science-related image and idea that appeared on screen and essentially established the role of content director in science television thereafter.

That so many in the scientific community today think back to *3-2-1 Contact* and smile is a wonderful testament both to the soundness of the Children's Television Workshop's vision of melding content with production in the development of the series and to Atkins's unique gifts in that arena.

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▶ **Ockert replies:** Ralph Smallberg brings up an excellent point. While some 1970s shows had science advisers, the Children's Television Workshop was one of the first production companies to give them a seat at the writers' table. In 1977 the company launched a three-day workshop in Glen Cove, New York, bringing together leading scientists and educators—including MIT physicist Philip Morrison—to brainstorm topics for what became *3-2-1 Contact*. From there, the Children's Television Workshop formed a formal science advisory committee for the show, intentionally including scientists from Black, Hispanic, and Asian American communities.

As I note in the article, the first content director of *3-2-1 Contact* was Charles Walcott, a biologist at the State University of New York at Stony Brook, who did a wonderful job of facilitating the collaborations between the scientists and the production staff. Likewise, Ted Ducas, a physicist at Wellesley College, deserves credit for his role in cowriting the show's excellent first season.

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Another look at the proton sea

Johanna Miller nicely summarizes the current experimental situation with the puzzling asymmetry of the proton's antiquark "sea" in the May 2021 issue of PHYSICS TODAY (page 14). She describes the SeaQuest experiment, which found that there are about 50% more $\bar{d}$ antiquarks than $\bar{u}$ antiquarks. The result is surprising, since the traditional mechanism generating the sea was commonly expected to be mediated by gluons, which are "flavor blind" and cannot tell $\bar{u}$ from $\bar{d}$.

Miller's report mentions two theoretical ideas proposed to explain the asymmetry. One is that the presence of two u valence quarks leads to "Pauli blocking" of sea u quarks, the twin brothers of $\bar{u}$ antiquarks. But quarks have six states available: three colors × two spin orientations. In addition, valence and sea quarks overlap little in momentum space. Pauli blocking is therefore way too small to explain the data. (I'll turn to the second idea—the contribution of the pion cloud—at the end.)

Unfortunately, Miller does not mention a third idea that has been put forth, which is more nontrivial and seems likelier to explain the puzzling asymmetry. It started with an observation by Alexander Dorokhov and Nikolai Kochelev[1] that the so-called 't Hooft effective four-quark Lagrangian[2] is "flavor nondiagonal," leading to processes $u \to u(\bar{d}d)$ and $d \to d(\bar{u}u)$ but not to $u \to u(\bar{u}u)$ and $d \to d(\bar{d}d)$.

In a way, the effect is also due to the Pauli exclusion principle, but at a different level. Topological tunneling events, known as instantons, create fields so strong that they fix the color and spin states of participating quarks uniquely. Instead of six possibilities, there remains only one, thus a complete blocking. Since the proton has two valence u quarks and only one valence d quark, that mechanism would suggest $\bar{d}/\bar{u} = 2$ rather than 1.

Recently I made the first attempt to evaluate that effect quantitatively, by calculating the wavefunction of the five-quark $uudu\bar{u}$ and $uudd\bar{d}$ sectors of the proton induced by the 't Hooft Lagrangian.[3] The results approximately match the data, in magnitude and momentum dependence.

How can one test that idea further? If that explanation is true, the sea of Δ^{++} baryons, which have three up quarks, would have only $\bar{d}$ antiquarks (at corresponding momentum fraction x). It is hardly possible to check that experimentally, but it can be tested numerically, via lattice gauge theory.

A second test is related to the other explanation Miller mentions, the pion cloud. While pions can indeed generate asymmetry in the isospin of the sea, they will not do so for the spin, since pions have spin zero. The 't Hooft Lagrangian, on the other hand, leads to strict predictions for the quark polarizations. For example, a left-handed up quark u_L can produce only a 100% polarized $\bar{d}_R d_L$ pair. Therefore, a key to the sea's antiquark asymmetry should come from future theoretical and experimental investigations that relate isospin and the spin asymmetry.

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2. G. 't Hooft, *Phys. Rev. D* **14**, 3432 (1976).
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Rare earths in space communications

I have enjoyed reading several items on the rare-earth elements in PHYSICS TODAY over the past few years. David Kramer's most recent piece focused on the topic (February 2021, page 20) was about neodymium-based rare-earth magnets, but readers might be interested to learn of another class of rare-earth magnets based on samarium. Among their applications are traveling wave tubes (TWTs), which form the backbone of the world's entire space communications system.

The core feature of most TWTs is a stack of samarium–cobalt ($SmCo_5$ or Sm_2Co_{17}) magnetic rings, each magnetized in opposition to its neighbor. One design uses a 25 cm stack of 16 rings that are 4 cm in diameter. The tubes can amplify and transmit millimeter waves in frequency ranges of 300 MHz to 50 GHz. They have bandwidths as high as two octaves, power gains of 40–70 dB, and output powers of a few watts to megawatts. TWTs also exhibit excellent reliability. *Voyager 1*, launched in 1977, has a SmCo TWT produced by Watkins-Johnson that is still broadcasting from more than 23 billion kilometers away from Earth!

The large communications satellites in geosynchronous orbit have around 20–50 TWTs that provide many essential services. Complete world coverage also requires satellites in polar orbits. Fortunately, Iridium Communications now maintains a constellation of 66 low-Earth-orbit communications satellites that are in polar orbits. The geosynchronous-orbit and low-Earth-orbit satellites, taken together, provide the world with access to space-based communications because of the discovery and development of $SmCo_5$ and Sm_2Co_{17} magnets in the late 1960s.

In 1966 Karl Strnat and Gary Hoffer reported finding promising magnetic properties in the yttrium–cobalt compound YCo_5. The following year, they and their colleagues reported the discovery of a new family of cobalt-based permanent magnet materials.[1] The researchers substituted other rare earths for Y and determined that $SmCo_5$ was the optimal choice for practical applications. Strnat and Alden Ray continued that line of study and ultimately discovered Sm_2Co_{17}, which has even more impressive magnetic properties. That research was possible only because a separation process developed by the Department of Energy's Ames Laboratory for the Manhattan Project made pure rare-earth elements available for the first time.

$SmCo_5$ and Sm_2Co_{17} magnets are superior to the platinum–cobalt magnets they replaced in terms of magnetic properties, cost, size, and weight. At present, they remain the only choices for many applications, particularly those that require very low or very high operating temperatures. Uses include gyros for space launch vehicles, brushless high-torque motors for dental and medical power tools, aircraft radar, and computer disk drives.

SmCo magnets have an extremely large coercive force, a measure of their ability to resist demagnetization, and an extremely large energy product (the maximum product of the **B** and **H** fields during demagnetization), a measure of their ability to do work. The maximum energy products for $SmCo_5$ and Sm_2Co_{17} are around 20 megagauss oersteds (160 kJ/m^3) and 32 MGOe (250 kJ/m^3), respectively. They are appropriate for operating at temperatures from absolute zero (−273 °C) to 300 °C for $SmCo_5$ and to 350 °C for Sm_2Co_{17}.

Importantly, the magnetic field SmCo magnets produce is parallel to the *c*-axis of their hexagonal unit cell and never flips to the easy basal plane at any temperature. The phenomenon, known as magnetocrystalline anisotropy, gives application designers great flexibility in magnet shape.

Neodymium-iron-boron magnets, discovered in 1984, have far better magnetic properties than $SmCo_5$ or Sm_2Co_{17} at ordinary temperatures. Their maximum energy product is about 55 MGOe (440 kJ/m^3), and their useful temperature range is between −138 °C and 150 °C. Therefore, NdFeB magnets are the only choice for moderate-temperature applications such as electric car motors or MRI devices. They have already replaced the superconducting magnets used in older MRIs, mitigating claustrophobia and size issues. $SmCo_5$ and Sm_2Co_{17} magnets, however, have far better magnetic properties than neodymium-iron-boron magnets at low temperatures and are the only choice for most space applications, such as TWTs. Thus, SmCo and NdFeB magnet technologies will coexist peacefully because their application areas do not overlap.

Reference

1. K. Strnat et al., *J. Appl. Phys.* **38**, 1001 (1967).

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Correction

September 2021, page 23—The story erroneously referenced a nonexistent radionuclide of iridium. The correct radionuclide is iridium-192. PT

Multiphysics Modeling Is Quickly Becoming Standard Practice in All Engineering Simulations

Phil Kinnane
VP of Sales, COMSOL

For all fields of engineering, simulation has been an important step in workflows from product design to their manufacture. As part of this, design engineers and modeling specialists have wrestled with the computing and solving capabilities of the day to produce more accurate and complex models. The complexity arises in part from the need to consider more details in a design's geometry, as these are integral to a better, more compact, and optimized design. In addition, taking more details of a design's physical behavior into consideration is usually required to increase its model's accuracy. Subsequently, in order to accurately simulate and optimize a design, the model needs to include all or many of the physics associated with the design's function, which includes its interaction with processes and its surrounding environment.

Coupling supplementary physics to engineering problems has been difficult because of the limitations imposed by traditional software. The software may be hardwired to simulate certain types of applications; it may be based on a set of questions used to define a single-physics phenomenon, such as electromagnetic fields around an antenna; or it may focus on a predefined coupled-physics phenomenon, such as thermal stresses in structural analysis. In some cases, the numerical method that is the basis for the software is not suitable for modeling the additional physics. Therefore, many simulations rely on assumptions, the exclusion of certain behavior, or the use of empirical data in order to consider the additional physics.

This is not to say that software strategies that are hardwired for such modeling are to be discounted. Much design work is adequately satisfied by the information such software provides. Yet multiphysics modeling is now opening up modeling possibilities, improving on current practices, and forging substantial inroads into the market once dominated by hardwired solutions.

Two reasons account for this growing dominance. The first is that certain applications are too difficult to simulate with hardwired software, because it does not allow the coupling of any arbitrary physics to any other. Thermal runaway in batteries is a great example of this, where the design engineer needs to couple most of the behaviors of a battery, which include electrochemical reaction kinetics, electric fields, chemical deposition, ionic transfer and electrical heat production, thermal stresses, and conjugate heat transfer within cooling. COMSOL Multiphysics®, on the other hand, satisfies this need quickly and effectively by providing flexibility in coupling these physics. It even has an add-on module specific for this type of modeling.

The second reason is that even in applications that were rather well served by hardwired simulation software, multiphysics modeling often provides greater accuracy and optimization as well as new knowledge about a product's design and manufacture. For example, electric-motor simulation software has primarily modeled just the electromagnetic field within motors. However, as high-power-density motors come into greater use, induction heating and thermal and other stresses can no longer be ignored; the design as a whole must be considered. In this case, multiphysics modeling with COMSOL Multiphysics® provides flexibility and expands the usefulness of these simulations by allowing the addition of arbitrary physics to existing analyses.

As the required complexity of engineering simulations continues to increase due to improvements in hardware capabilities and the numerical methods used to solve them, multiphysics modeling in product design and manufacture is quickly becoming established practice in engineering simulations.

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A cryogenic circuit cools from afar

A cloud of ultracold ions can lower the temperature of a trapped proton 9 cm away.

Much of modern experimental atomic physics relies on a counterintuitive principle: Under the right circumstances, zapping matter with a laser doesn't inject energy into the system; rather, it sucks energy out. By cooling the system to a fraction of a degree above absolute zero, one can observe quantum effects that are otherwise hidden.

Laser cooling works like a charm, but only when a system's ladder of quantum states contains a transition that the lasers can repeatedly and reliably cycle to leave the system with a bit less energy each time. Atoms of alkali metals and a few other elements are ideal. Molecules are much more challenging: Their vibrational and rotational degrees of freedom create a multitude of low-lying quantum states that can disrupt a cooling cycle. And fundamental particles such as protons, which lack internal states altogether, can't be laser cooled at all.

Nevertheless, there's a lot of interest in experimenting on fundamental particles at low temperature. Toward that end, researchers from the Baryon Antibaryon Symmetry Experiment (BASE) collaboration have now demonstrated a method for using a cloud of laser-cooled ions to cool a single proton, even when the proton and ions are too far apart to directly interact.[1] Figure 1 shows team member Matthew Bohman in the lab at Johannes Gutenberg University Mainz in Germany. By coupling both the proton and the ions to an inductor–capacitor (*LC*) circuit, they transport the effect of the laser cooling from one location to the other.

Try, try again

BASE, as the full name suggests, seeks to compare the properties of protons with those of antiprotons to test how exact the symmetry between matter and antimatter really is. In particular, the goal is to measure the magnetic moments, or *g* factors, of each particle by observing the spin flips of a single particle held in an electromagnetic Penning trap. Team members in Mainz work on measuring the proton *g* factor, while collaborators at CERN work on antiprotons.

The experiments require particles cooled to between 100 and 500 mK. "Warmer than that, and the spin states get muddled together," explains Christian Smorra, leader of the Mainz group. So far, the researchers have achieved those temperatures by a technique called resistive cooling. As the proton oscillates back and forth in its trap, the moving charge induces a tiny current, called an image current, in the trap electrodes. The current is allowed to flow into an external circuit, where its energy is dissipated, and the proton energy steadily decreases.

The energy flow, however, goes both ways. Thermal noise in the circuit creates voltage fluctuations in the trap electrodes; the fluctuating electric potential jostles and warms the proton. The circuit is cooled with liquid helium to 4 K, so it might seem that the researchers can't resistively cool their proton any further than that.

But they can—using a trick that capitalizes on the definition of temperature and the fact that the trap contains only one proton. An ensemble of particles at a given temperature is spread among states of different energies, according to the Boltzmann distribution. So a single particle in a thermalized system hops among states, and at any given instant its energy might be higher or lower. When the BASE researchers abruptly disconnect their trap from the circuit, they lock the proton into whatever state it is in at the time. That state, with a few percent chance, could be low enough in energy for a *g*-factor measurement.

It's possible, then, to "cool" the proton to a significantly lower temperature than its surroundings, just by connecting and disconnecting the trap enough times until the proton is caught in a low-energy state. The process doesn't take long—about an hour. But a full *g*-factor measurement campaign requires 1000 cold-proton measurements, which means that a solid month or more of experiment time might be spent just waiting for the particle to find its way into a cold enough state.

FIGURE 1. MATTHEW BOHMAN examines the core of the BASE collaboration's new cooling apparatus. The central gold-colored cylinder contains two electromagnetic Penning traps: one to hold laser-cooled beryllium atoms, the other to hold a single proton. (Photo by Stefan F. Sämmer, Johannes Gutenberg University Mainz.)

Cooling from a distance

To speed things up, the BASE team turned to an idea proposed 30 years ago by David Wineland and Daniel Heinzen: using laser-cooled ions in one trap to sympathetically cool a proton in another trap.[2] The trap electrodes are wired together, and as before, energy is exchanged via the induced image currents: from the proton to the trap electrodes to the ions, where it's promptly laser cooled away.

It's essential that the laser-cooled particles be ions, not atoms: Only charged particles can be confined in a Penning trap and couple to the image currents. The researchers chose singly charged beryllium ions, which have the same electronic configuration as neutral lithium atoms and are thus among the most easily laser cooled of all species. A single laser can cool a cloud of Be^+ ions to 0.5 mK, so in principle, the proton could reach a temperature almost as low.

The proton cooling is still slow. For particles in the two traps to exchange energy, they need to oscillate in their traps at identical frequency. The oscillation frequency depends on each trap's electric potential, which is hard to keep perfectly stable. The laser-cooled Be^+ ions might therefore be cooling the proton for only a fraction of the time that the traps are connected.

The innovation in the new work was to also wire in the *LC* circuit, as shown in figure 2a. When the circuit's resonant frequency matches the frequency of both traps, the current—and thus the rate of energy exchange—is amplified by the circuit's quality factor *Q*. The BASE collaboration uses high *Q*-factor circuits for its other experiments, and its researchers are good at making them. The *Q* factor of the circuit used in the proton-cooling experiment, 15 000, is typical of their work.

The drawback is that, once again, the thermal noise in the circuit leaks into the traps and heats the particles. Still, because the laser-cooled Be^+ ions are continuously cooling the proton at the same time as the circuit is heating it, the system can settle into a steady state with the proton much colder than the circuit.

Resonance upon resonance

To monitor the system, the researchers read out the circuit's noise spectrum, as shown in figure 2b. The widest bump is the whole *LC* circuit resonance—although it looks broad in the figure, it is needle-thin relative to the resonant frequency of 479 kHz. The proton and Be^+ resonances both take bites out of the circuit-noise bump as a sharp spike and a slightly wider dip, respectively.

The researchers use the spectrum to verify that the resonant frequencies all match. They also use it to track the proton's temperature. Typically, in experiments on trapped particles, it's desirable for the trap potential to be as close to perfectly harmonic as possible. Then, the particles oscillate at the same frequency no matter their energy. But here, the researchers deliberately made the proton trap slightly anharmonic. As the proton cools, its frequency shifts.

The frequency-spectrum measurements revealed that the proton was cooled to 2.6 K. Relative to the 100–500 mK needed for a *g*-factor measurement, that number might seem unimpressive. But the fact that it's more than 80% lower than the *LC* circuit temperature of 15 K is an encouraging demonstration that image-current cooling is possible.

The *LC* circuit was cooled with liquid helium at 4 K; its temperature was so much higher than that because it was heated by the amplifier that was used to read out the noise spectrum. Under the best of circumstances, that heating is limited to a couple of degrees. But as an amplifier ages, the heating problem worsens.

"It just happened that by the time we got everything else working, the amplifier was old," says Smorra. "That's experimental physics for you." Swapping out the amplifier for a new one will reduce the whole system's temperature by a factor of 3—not quite low enough for a *g*-factor measurement.

The BASE researchers expect that the essential improvement could come from tinkering with the trap frequencies. In the proof-of-principle experiment, both traps were tuned to the peak of the *LC* circuit's resonance. That arrangement maximizes the rate of energy exchange between the two traps, but it also maximizes the rate of heating from the circuit; detuning the frequencies slightly would decrease both rates. Detuning too much, of course, will negate the advantage of using the circuit in the first place. But in between, there's a range where the sympathetic-cooling rate should have enough of an advantage to push the proton to the desired temperature.

"Once we optimize the setup, 100 mK certainly seems possible," says Bohman,

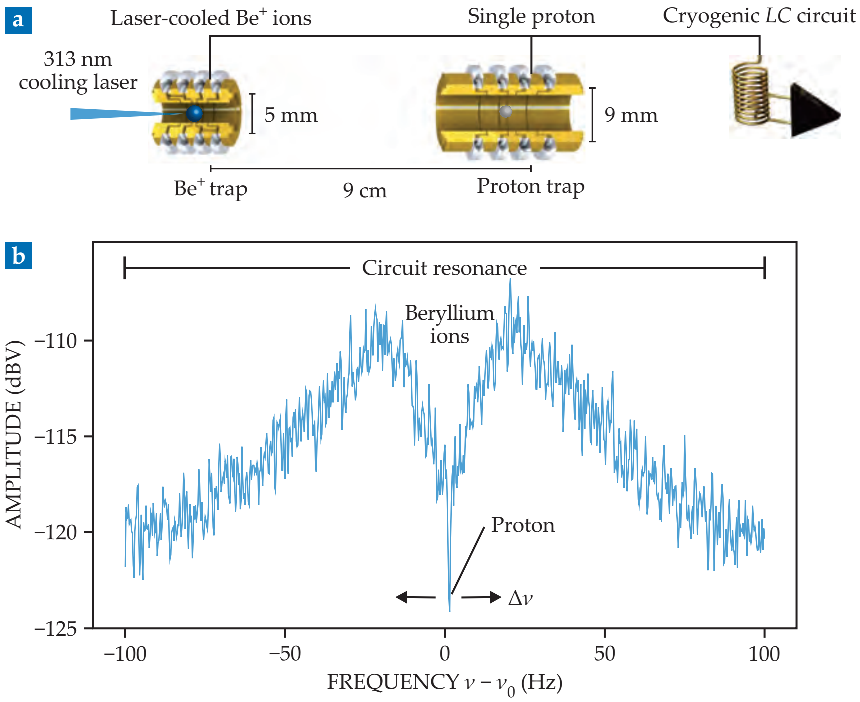

FIGURE 2. AN INDUCTOR–CAPACITOR (*LC*) circuit **(a)** amplifies the rate of energy transfer between a pair of Penning traps 9 cm apart, so the laser-cooled beryllium ions in the first trap can sympathetically cool the proton in the second trap in just seconds. **(b)** The circuit's noise spectrum contains a bump at the circuit resonant frequency ν_0 = 479 kHz, with nested dips marking the Be^+ and proton resonances. The proton trap is slightly anharmonic, so as the proton cools, its resonant frequency shifts. (Adapted from ref. 1.)

"and even below that is maybe something we can do."

Beyond protons

An *LC* circuit isn't the only possible way to use one set of trapped particles to cool another. The most straightforward approach is to put both sets of particles in the same trap, where they can directly exchange energy and approach a common thermal equilibrium. Another possibility other researchers are exploring is to keep the particles in separate traps but bring those traps close enough together that the particles can exchange energy through their Coulomb interactions.

The big advantage of the circuit-mediated approach, though, is its adaptability. Because the particles in their respective traps never come close together, it doesn't matter if they attract or repel, chemically react, or even annihilate each other.

The flexibility bodes well for the BASE collaboration's experiments of interest, in which they hope to cool antiprotons just as easily as they cool protons. The antiproton setup could use the same positively charged Be ions as in the proton setup; the only necessary change would be to reverse the antiproton trap's electric potential to account for the particle's negative charge.

But the possibilities don't end there. Molecules of two or more atoms, when cooled into the quantum regime, offer a range of ways to test fundamental physical laws (see the article by Dave DeMille, PHYSICS TODAY, December 2015, page 34). Molecules are challenging to laser cool, but molecular ions could lend themselves to cooling through the *LC* circuit.

Another possible target is highly charged ions, of interest for testing the theory of quantum electrodynamics (see PHYSICS TODAY, December 2012, page 22). Most highly charged ions lack a convenient laser-cooling transition. But, Smorra predicts, they should be easy to cool with the circuit-mediated method. "In fact, it would be even easier," he says, "because the image current, and therefore the interaction strength, is enhanced by a factor of the charge."

Johanna Miller

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A new undersea volcano is born east of Africa

Geophysical and oceanographic observations establish how a deep magma chamber fueled an extraordinary eruption.

The largest submarine volcanic eruption ever recorded began on 10 May 2018 off the eastern shore of Mayotte, one of the Comoros group of islands east of Mozambique and north of Madagascar. Then and there, a highly viscous and ductile volume of molten rock from the asthenosphere—Earth's upper mantle—pierced the cooler and brittler lithosphere above it and erupted lava onto the seafloor.

That day, people in Mayotte felt a magnitude 4.3 earthquake, the first of many. The largest event, of magnitude 5.9, struck several days later, on 15 May. Over the next few weeks, the moving magma generated a few very low frequency earthquakes in the crust and thousands of deeper ones.[1] The result of all that geophysical activity was a new mountain on the seafloor. (To learn about other submarine volcanoes, see PHYSICS TODAY, August 2012, page 16.)

As the chief scientist of the May 2019 research cruise MAYOBS 1, Nathalie Feuillet of the Paris Institute of Earth Physics (IPGP) and the University of Paris led an effort to collect seismic and surface deformation data of the volcanic eruption and the ongoing earthquakes. (Mayotte is an overseas department of France.) She and her colleagues—from institutions including the French geological survey BRGM, the CNRS, and the French Research Institute for Exploitation of the Sea—found that the new undersea volcano now stands 820 m tall and lies at the end of a 50 km ridge formed by a series of recent lava flows.[2] The geological feature is likely part of a tectonic structure formed by fissures and faults associated with the East African Rift to the west.

FIGURE 1. JÉRÉMY GOMEZ of the Paris Institute of Earth Physics (IPGP) helps retrieve an ocean-bottom seismometer that was deployed off the eastern coast of Mayotte, an island north of Madagascar. He and several other scientists participated in a May 2019 research cruise to collect geochemical, seismological, and seafloor topographic data after the region began experiencing volcanism and earthquakes in May 2018. (Courtesy of Eric Jacques, IPGP.)

Seafloor anomaly

The occurrence of the 2018 eruption was unusual. No volcanic activity had ever been reported in the area before, and over the past 30 years geologists had cataloged just two small earthquakes near Mayotte, according to an earthquake database maintained by the US Geological Survey. The BRGM recorded the initial seismic activity associated with the 2018 eruption using a single seismic station on Mayotte. With their sparse observations, the BRGM suspected the earthquakes originated somewhere in the ocean east of Mayotte but couldn't pinpoint the exact source of the tremors.

Shortly thereafter, Feuillet and other volcanologists and seismologists made plans to study the region more closely. Among other activities, they installed ocean-bottom seismometers (OBSs), instruments capable of picking up undersea earthquake activity. (For more on those devices, see "Deploying seismometers where they're needed most: Underwater," PHYSICS TODAY online, 24 May 2019.) By the end of 2018, the project was finalized, and Feuillet and some colleagues traveled to Mayotte in February 2019 to deploy the OBSs.

The discovery of the volcano came in May 2019 when the MAYOBS 1 research cruise recovered the OBSs deployed in February; one of the devices is shown in figure 1. The researchers on the ship used a multibeam echo sounder to bounce sound waves off the ocean floor across an area of 8600 km^2, slightly smaller than the size of Puerto Rico, to determine the seafloor elevation. An instrument deployed to more than 3000 m below the ocean surface looked for some trace of volcanic activity by determining the seawater's conductivity, temperature, and chemical composition as a function of depth. Absolute pressure gauges attached to the OBSs measured the vertical deformation of the seafloor.

"One evening we saw a big anomaly on a polar echogram of the water column," says Feuillet, recalling the cruise. "It was a 2000-meter-high acoustic plume." East of Mayotte, the source of the anomaly turned out to be a mixture of solid particles, liquid droplets, and bubbles. The jet of materials had the telltale characteristics of volcanism: highly turbid, alkaline water and elevated concentrations of molecular hydrogen, methane, and carbon dioxide. "It was one of the biggest acoustic plumes ever detected in the water column," says Feuillet. The volcano, which had formed 10 months earlier, was erupting again.

A fuller picture of the volcano and its surroundings emerged when the seafloor topography data revealed the Mayotte volcanic ridge. A previous research cruise, led by the French Naval Hydrographic and Oceanographic Service, had fortuitously mapped the same stretch of seafloor in 2014. Figure 2a shows what was once the relatively flat seafloor topography; figure 2b, the new undersea mountain and ridge.

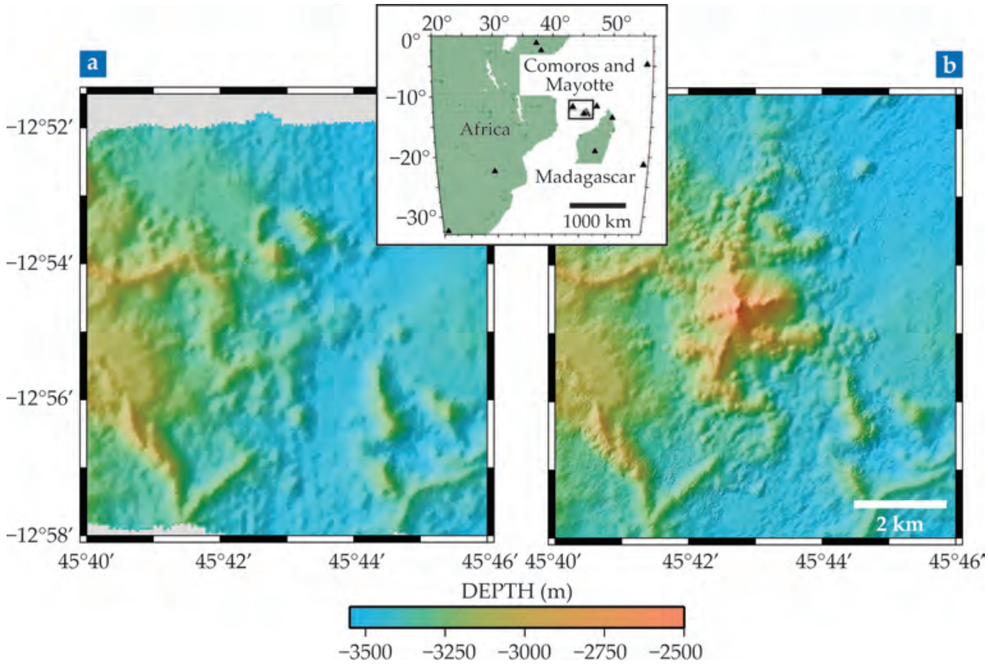

FIGURE 2. A NEW VOLCANO formed east of the East African Rift off the eastern shore of Mayotte after lava erupted through the seafloor in mid 2018. **(a)** This elevation map from measurements collected during a 2014 oceanographic research cruise, shows a relatively flat seafloor topography. **(b)** More recent data from a 2019 cruise and seismic stations (black triangles in inset) reveal the formation of an undersea volcanic ridge. (Adapted from ref. 2; inset from ref. 3.)

Seismic swarm

To learn more about the new volcano, which spewed about 5 km^3 of lava during the 2018 eruption, coauthors Wayne Crawford and Jean-Marie Saurel of IPGP and the University of Paris and other seismologists on the team analyzed the seismic-wave data collected by a network of seismometers on land and on the seafloor; most of them were installed or deployed after the 2018 eruption.

From 25 February to 6 May 2019, the network detected some 17 000 earthquakes, 94% of which cluster on the western segment of the Mayotte ridge and 25–50 km below the seafloor. An additional 84 earthquakes were identified by IPGP and University of Paris coauthors Claudio Satriano, Angèle Laurent, and Pascal Bernard as very low frequency events lasting up to about 30 minutes, with seismic-wave energy detected below 0.10 Hz. The very low frequency earthquakes can be generated by a seismic source that's been repeatedly excited, possibly faults destabilized by magma from the upper mantle that pressurize a large deep reservoir.

To have so many earthquakes deep in Earth's interior is rare. Many seismic events caused by volcanic activity occur in the brittler crust rather than the deeper, more ductile mantle. At Mayotte, the crust descends about 17 km below the surface. Below that brittle–ductile transition zone, molten rock more easily deforms and is therefore less likely to crack and instigate tremors in response to seismic energy.

Still, Feuillet and her colleagues suspect that magma activity may have caused the deep earthquakes that were observed below Mayotte. Most of them were clustered beneath a caldera structure, a large, low topographical region that formed when an ancient volcano erupted and collapsed. The many faults and fissures of the caldera form channels through which the magma could have easily navigated from a deep upper-mantle reservoir to the seafloor.

The researchers infer that the Comoros archipelago, with the African continent to the west, is part of a tectonic zone where the crust is pulling and sliding apart. Some earthquakes could be the result of the transfer of tectonic deformation from the East African Rift to an area of Madagascar with rifting in the crust.

As the region stretches, the lithosphere is susceptible to fracturing, which provides more pathways for the magma to reach the surface. Once the magma travels through the weakened crust and reaches the seafloor, it can instigate swarms of deep earthquakes. That interpretation is supported by another recently published paper by Océane Foix, Feuillet, and their colleagues. They used a tomographic method to construct a more detailed picture of the new volcano's plumbing.[3]

Early warning

The new volcano is 50 km east of Mayotte. Feuillet and her colleagues suspect that the main magma reservoir is 5–10 km east of the island and about 70 km below the seafloor. Another eruption from the reservoir, if it's closer to the island, could be more dangerous than the last one. The next goal is to develop a warning system that would alert everyone in the region, especially Mayotte's 270 000 residents, of a future eruption as early as possible.

On land, GPS instruments and seismometers are collecting real-time data. But a permanent underwater observatory closer to the source would provide better-quality measurements. Newly funded instrumentation includes submarine pressure gauges to more closely monitor how the seafloor deforms in response to subsurface magma activity.

Feuillet and other colleagues have organized several cruises to Mayotte to collect data and monitor the ongoing seismic and volcanic activity. Under a new research framework named the Mayotte Volcanological and Seismological Monitoring Network, scientists are keeping the residents and leaders of the islands informed of the evolution of the situation through monthly bulletins, daily reports, and a Facebook page.

A January 2021 cruise found evidence of new lava flows, but when Feuillet and her team returned in May, that flow had stopped. They've since measured some seismic activity and surface deformation, although at a much lower rate. Feuillet says, "We are still monitoring this area to better understand if the eruption is continuing or not at the site of the new volcano."

Alex Lopatka

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An unusual material hosts both even and odd superconducting phases

The heavy-fermion crystal combines properties of systems that have inversion symmetry and of those that break it.

Unconventional superconductors—those that the Bardeen-Cooper-Schrieffer theory can't explain—typically have a single superconducting phase. That's surprising because their conduction electrons have various theorized ways to couple up, whether through different mediators or in different spin states of the Cooper pairs. Conceivably, they could transition between different sorts of superconducting orders. But so far, only uranium ditelluride and a few other materials have shown such transitions.

Most of those compounds with multiple superconducting phases are heavy-fermion materials. Like other heavy-fermion materials, their strongly correlated electronic behavior arises from the partially filled 4*f* and 5*f* orbitals of their rare-earth or actinide ions. Electrons in those orbitals hybridize with conduction electrons to produce quasiparticles of large effective mass—anywhere from 50 to 1000 electron masses. The quasiparticles are too heavy to interact much with the crystal lattice and its phonons, so they can't form Cooper pairs via the phonon-mediated mechanism of conventional superconductors. Nonetheless, many heavy-fermion materials are superconducting; in fact, they're one of the largest and most varied classes of unconventional superconductors.

Now Elena Hassinger of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany, and the Technical University of Munich and her colleagues have observed two superconducting phases in the heavy-fermion material $CeRh_2As_2$. Unlike the phases in UTe_2, the ones in $CeRh_2As_2$ appear to have different parities as a result of the material's particular lattice symmetry.[1]

Growing interest

The $CeRh_2As_2$ study began a few years ago when then-postdoc Seunghyun Khim (now a leader of the material design and synthesis group at the Max Planck Institute for Chemical Physics of Solids) and Christoph Geibel were growing rare-earth and nitrogen-family compounds in the hopes of finding correlated quantum systems. For each crystal they grew, they characterized the structure and some basic properties, such as resistivity and specific heat, with the help of Manuel Brando's group, also at the Max Planck Institute for Chemical Physics of Solids.

Although $CeRh_2As_2$ was first synthesized in 1987, no physical properties beyond the structure had been reported in the intervening years. To the Dresden researchers, the resistivity appeared typical for a heavy-fermion material, at least at first.

In their specific-heat measurements, however, three notable behaviors emerged. First, the material's specific heat increased with decreasing temperature according to a power law, a trait that suggested the proximity of a quantum critical point, which is a phase transition at absolute zero temperature (see the article by Subir Sachdev and Bernhard Keimer, PHYSICS TODAY, February 2011, page 29).

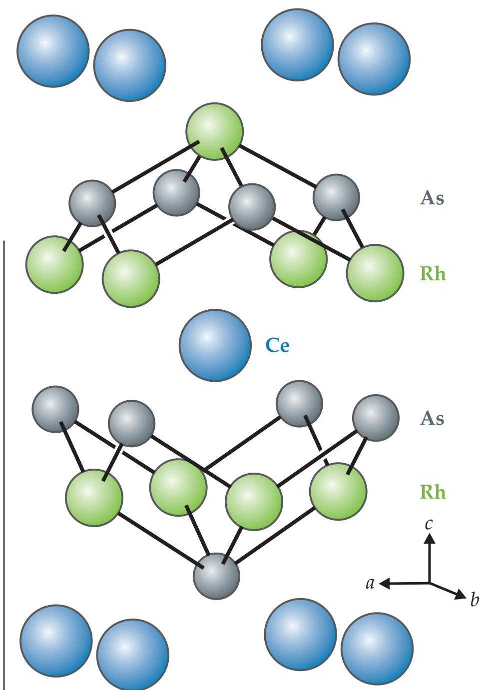

FIGURE 1. $CeRh_2As_2$ is an example of a heavy-fermion material: It hosts quasiparticles with masses up to 1000 times as large as those of electrons. Within its layered structure, each cerium atom (blue) is sandwiched between blocks of rhodium (green) and arsenic (gray) atoms. Although the material has overall inversion symmetry, the structure isn't inversion symmetric in the vicinity of the Ce atoms because of the different structures of the Rh–As layers above and below. That lack of local inversion symmetry seems to influence the material's superconducting behavior. (Adapted from ref. 1.)

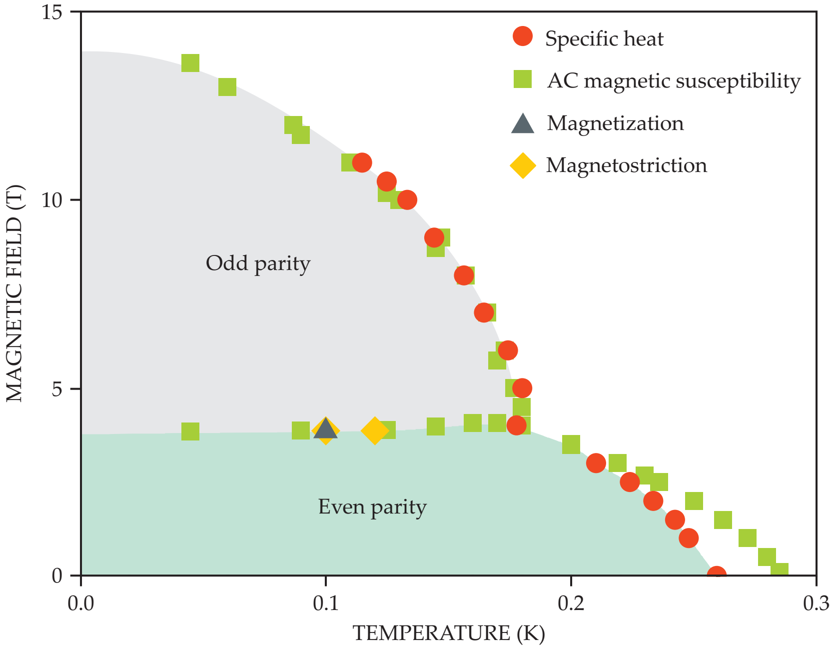

FIGURE 2. THE PHASE DIAGRAM for $CeRh_2As_2$ shows two superconducting phases. Experimental signatures of the phase transitions as a function of temperature and magnetic field come from various measurements indicated by the symbols. The material is one of only a few known to have two superconducting phases. What's more, $CeRh_2As_2$ hosts states with different parities, including the unusual odd-parity, or spin-triplet, superconducting state. (Adapted from ref. 1.)

Also notable were deviations from the power law, which sometimes indicate a phase transition. The researchers noticed two: a small bump at 0.4 K from some as-yet-unidentified phase transition and a spike at 0.3 K. A drop to zero in the resistivity around the same temperature led the researchers to conclude that the second transition marked the onset of superconductivity.

The microscopic behavior underlying the three observations was unclear, and Hassinger and her colleagues weren't sure what behavior to tackle first. They decided to start by establishing the electronic band structure. To do so, they looked for what are known as quantum oscillations. In a time-varying magnetic field, the quantized energies of the material's resulting Landau levels sometimes match the Fermi level. Those oscillations in the number of electron states at the Fermi level affect the magnetic susceptibility, the resistance, and other properties.

Hassinger's then-postdoc Javier Landaeta measured the AC magnetic susceptibility on a setup the group built in 2019. The equipment can reach extreme conditions—temperatures as low as 20 mK and magnetic fields up to 15 T—all with low levels of noise. Unfortunately, the researchers didn't see any oscillations in $CeRh_2As_2$, perhaps because the sample wasn't quite pure enough for such observations. They did, however, notice what seemed to be a phase transition inside the superconducting state.

The next phase

To confirm that the phase transition wasn't an artifact or error in their experiment, Hassinger and her collaborators performed an extensive series of measurements to assemble a full phase diagram. They found that when the magnetic field was applied in the material's *ab*-plane (see figure 1), $CeRh_2As_2$ didn't show signs of multiple phases, and a magnetic field of less than 2 T forced it out of the superconducting phase.

But when the field was applied along the *c*-axis, the material remained superconducting in fields of up to 14 T, despite its fairly low transition temperature of 0.26 K. Typically, a superconducting state that's easily destroyed by thermal energy will likewise be vulnerable to having its Cooper pairs twisted apart by a magnetic field. The $CeRh_2As_2$ crystal's ratio of critical field (the highest magnetic field the superconducting phase can withstand) to critical temperature is an order of magnitude larger than that of most unconventional superconductors.

The critical temperature decreased with increasing magnetic field, but around 4 T the rate at which it decreased suddenly slowed down, as shown in figure 2. The researchers suspected that the abrupt change signaled the transition between two distinct superconducting phases.

The full suite of experimental techniques supported that conclusion. They all showed a kink at 4 T, and the resistivity stayed zero throughout. One of the superconducting phases appears only when induced by a *c*-axis magnetic field.

One superconducting state (light green region of figure 2) disappears at a field of about 4 T, when the energy splitting between spin-up and spin-down electrons becomes larger than the Cooper-pair binding energy, a phenomenon known as Pauli suppression. But Pauli suppression is absent for the second superconducting state (gray region). Such absence usually occurs in a triplet state when the spins in the Cooper pairs point in the same directions. In that case, the magnetic field and Zeeman splitting can't break them apart. (See the article by Anne de Visser, PHYSICS TODAY, November 2020, page 44.)

The rich phase diagram was a surprise. "Finding a new class of superconductor was not expected," says Hassinger. "We expected to see behavior typical of a Ce heavy-fermion system and hoped to find quantum critical behavior."

Odd results

The researchers tentatively attribute the superconducting behavior in $CeRh_2As_2$ to the material's symmetry. Overall, the material has inversion symmetry, but as is the case in any lattice, that symmetry holds true only about certain points. The layers of Ce atoms (blue in figure 1) are alternately separated by Rh–As layers (green and gray) with the same structure but the atom positions swapped. Because the Rh–As layers differ, inversion symmetry is absent in the vicinity of any given Ce atom and its 4*f* electrons that dictate much of the material's electronic behavior.

As a result, the crystal's orientation-dependent magnetic response some-what resembles that of noncentrosymmetric superconductors, which lack inversion symmetry. Broken inversion symmetry leads to commingling even-parity and odd-parity superconducting phases, which are composed of Cooper pairs in spin-singlet states and spin-triplet states, respectively. That mixture leads to Pauli suppression by in-plane fields but not by out-of-plane fields. Such materials, however, lack multiple superconducting phases.

Centrosymmetric materials, on the other hand, have superconducting phases that are either even or odd parity, and a transition between the phases could be possible. $CeRh_2As_2$ combines the magnetic anisotropy of noncentrosymmetric materials with the single-parity phases of centrosymmetric materials.

A similar result had been predicted in 2012 in models for generic bilayer materials.[2] In the models, interlayer hopping and intralayer Rashba interactions—the combined effect of spin–orbit interactions and an asymmetrical lattice potential—lead to a magnetic-field-driven transition between even- and odd-parity phases.

To adapt a similar model to their system, Hassinger's group partnered with theorists Daniel Agterberg of the University of Wisconsin–Milwaukee and Philip Brydon of the University of Otago in New Zealand. The model Hamiltonian, which captured the Ce ion's local lattice asymmetry, replicated the experimentalists' findings, including that one phase isn't subject to Pauli suppression from fields along the *c*-axis. It also predicted that in $CeRh_2As_2$, as in the bilayer system, one of the superconducting phases should be even parity and the other should be odd parity, a rare type of superconductivity found in some ferromagnetic superconductors and UTe_2. (Unlike in $CeRh_2As_2$, the superconducting phases in UTe_2 are all spin-triplet states.[3])

Odd-parity superconductivity is of interest in part because it may be topological. Such states derive their behavior from the connectedness of the band structure rather than from its symmetry, and among many unusual properties, they are robust against defects. Topological states could potentially be useful for applications such as topological quantum computing (see the article by Sankar Das Sarma, Michael Freedman, and Chetan Nayak, PHYSICS TODAY, July 2006, page 32).

Although the theory and experimental results are consistent, Hassinger and her colleagues' work thus far isn't conclusive as to the fluctuations that mediate Cooper pairing in $CeRh_2As_2$. Clues to that puzzle may lie in the nature of the unknown phase at temperatures just above the superconducting transition. The researchers' latest work suggests that the state may be an unusual quadrupole density wave,[4] and how it competes or coexists with superconductivity remains to be explored.

Heather M. Hill

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PT

A sprinkling of scientists prioritizes behaviors to counter climate change

Can steps like less travel and more talk advance science and serve as an example to the public?

"Plenty of people believe humans could move to another planet," says Adrienne Cool, a professor at San Francisco State University who studies globular clusters. "That narrative is out there, and part of our job as astronomers is to counter it, to make clear that there is no Planet B." A few years ago, Cool was "struggling with the contrast of spending time and mental energy thinking about things that are so far away when what's happening here on Earth is so urgent." She, colleagues, and students resolved to work toward climate sustainability.

Meanwhile, in June 2019, astronomers in Europe gathered for a conference in Lyon, France, recalls Leo Burtscher, a staff astronomer at Leiden University. "There was a heat wave, and a group of us started talking about high temperatures being the new normal and how we are contributing to climate change," he says. "I see it as irresponsible, ethically and professionally, to burn fossil fuels for astronomy." Over Twitter, the group launched a sustainability movement for astronomers.

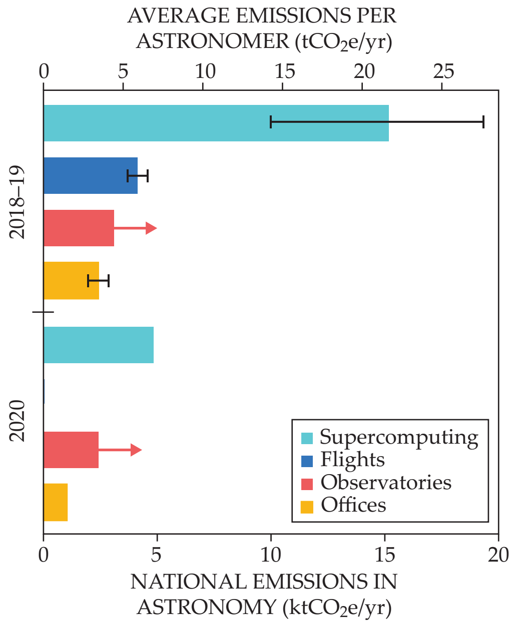
In October 2019 the nascent grassroots organizations in the US and Europe merged to form Astronomers for Planet Earth. A4E now has more than 1300 members in 73 countries. The group seeks ways for astronomers to minimize their discipline's contributions to climate change and to serve as role models for other academics, students, and the public.

In fall 2018, scientists in France formed Labos 1point5, a group that is working to mitigate climate change at individual, institutional, and political levels. The group's name refers to the 2015 Paris Agreement's goal of limiting the rise in average global temperature above preindustrial temperatures to 1.5 °C (see, for example, "Paris carbon cuts are insufficient, UN report warns," PHYSICS TODAY online, 22 November 2016). Absent extraordinary measures, the world is on track to warm by 3.3–5.7 °C by the end of the century, according to part 1 of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which was released in August.

Olivier Berné is an astronomer who works in Toulouse at the Research Institute in Astrophysics and Planetology of the CNRS. He's also the cofounder of Labos 1point5 with agronomist Tamara Ben Ari of the French National Institute for Agriculture, Food, and Environment (INRAE) in Paris. "We saw a paradox," Berné says. "As scientists, we were well aware of climate change, yet we didn't change our behavior to take it into account." The group grew to more than 1000 members across academic fields after it published an op-ed in *Le Monde* in March 2019.

Around the world, pockets of individual scientists and institutions are taking steps to counter climate change. They are estimating carbon footprints, setting up remote conferences, designing greener facilities, and switching to plant-based

THE BLUE MARBLE. Scientists and their institutions are mobilizing to avoid the worst predictions for the planet if climate change continues unabated. (Composite image by NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring.)



ESTIMATING CARBON FOOTPRINTS is a first step toward lowering them. The plots show total national emissions in astronomy and average emissions per astronomer in Australia in 2018–19 (upper bars) and in 2020 (lower bars); the units are tons of CO_2 equivalent per year. Emissions decreased because of the ongoing grounding of air flights during the COVID-19 pandemic and the switch by some of Australia's supercomputer centers to renewable energy. The arrows on the red bars indicate lower limits because data from observatories were incomplete. (Courtesy of Adam R. H. Stevens.)

cafeteria meals—estimates depend on production practices and other factors, but a vegan diet has roughly half the carbon footprint of an omnivorous one. They are also working to elevate such activities from the spotty to the systemic.

"We as scientists understand what climate scientists are saying. If we do not take seriously what our colleagues are saying, then why should the public?" says high-energy physicist Valerie Lang, a junior faculty member at the University of Freiburg in Germany.

Quantifying emissions

A first step for many scientists and institutions has been to estimate their own carbon footprint. "If we don't have numbers, we can't draw conclusions or know where to focus our attention," says Lang, who heads the sustainability initiative for Germany's association of young high-energy physicists.

Knud Jahnke, a staff astronomer at the Max Planck Institute for Astronomy in Heidelberg, Germany, first did a carbon assessment for the institute a decade ago. He did another in 2018, inspired, he says, by activist Greta Thunberg. He found that the main areas to focus on to reduce emissions are air travel, heating, and electricity consumed by supercomputing. Heating is an infrastructural issue that scientists can't easily change, Jahnke notes. So, he says, "what do we do about traveling and electricity?"

Members of Labos 1point5 created a tool to estimate carbon footprints (https://labos1point5.org/ges-1point5). More than 270 labs in France have used it. For most of the 70 labs that have already completed the calculation, emissions are mainly from commuting, heating, and traveling. But the results, Berné says, are "surprisingly heterogeneous from one lab to another. That means providing top-down solutions won't work. Reductions in emissions have to be done at the local level."

Robin Arsenault, who heads the European Southern Observatory's sustainability project, says that ESO emits an estimated 28 000 tons of carbon dioxide per year. The main contributors are electricity consumption, which includes heating, cooling, and powering computers and servers; travel, including staff commutes to work and flights to meetings and to the observatory's telescopes in Chile; and indirect emissions originating with the goods and services it purchases. "None of this is an exact science," he cautions. "The error bars are large. Absolute accuracy is not critical. The important point is to monitor and reduce emissions."

"Organizations often get hung up on quantifying emissions and setting targets," says Claire Hoolohan, a research fellow at the University of Manchester's Tyndall Centre for Climate Change Research who is looking at how UK universities are responding to climate change. While estimating carbon footprints can be useful, she says, "immediate action" is needed.

UK universities have worked for years to reduce campus energy use, says Hoolohan, and are increasingly considering other sources of emissions. Food service is one area where emissions reductions are being made. The Tyndall Centre switched to serving only plant-based foods a few years ago, for example, and some universities have stopped serving red meat. The COVID-19 pandemic has created opportunities to revamp academic practices and priorities, she notes. "Moving forward, it's about trying to grapple with complex issues and cultural challenges."

Modifying mentality

Even before the pandemic, a handful of scientists had begun experimenting with new meeting models. Rachel Grange, a photonics physicist at ETH Zürich in Switzerland, and Martha Merrow, a chronobiology researcher based in Munich, Germany, had each organized international remote meetings that featured hubs for people in the same city to attend together. In addition to reducing travel, such conferences are more accessible to people with small children, those who can't afford travel, and those who struggle to obtain visas. (See PHYSICS TODAY, September 2019, page 29.)

A growing number of institutions and funding agencies in Europe now require that travel within certain distances be by train. And some institutions have set goals to reduce their carbon footprints. In 2017, for example, an analysis at ETH Zürich found that business trips account for more than half the university's greenhouse gas emissions. The university set itself a target to reduce per capita emissions by 11% by 2025.

Supercomputing also contributes significantly to the carbon footprint in many scientific fields. Simon Portegies Zwart, a computational astrophysicist at Leiden University, notes that supercomputers are not always necessary. "A decade ago I would have used the biggest toy I could access," he says. "Now, if I can do my science on my laptop, I do. The power consumption of a typical high-powered laptop is between 12 and 45 watts, which is negligible compared to the power demands of a supercomputer." Sometimes that means getting a lower-resolution result, he concedes. "I might get results to more decimal points with a supercomputer, but that doesn't mean the results are scientifically better."

Often, says Portegies Zwart, code could be optimized so that running it on a supercomputer would be faster and consume less energy. "But the only real


PAWSEY SUPERCOMPUTING RESEARCH CENTRE

NEW SOLAR PANELS generate 118 kW at the Pawsey Supercomputing Research Centre in Perth, Australia. That is sufficient to power with net zero emissions a cooling system based on groundwater.

solution is to use renewable energy."

For a decade or so, some supercomputing facilities have diverted excess heat to warm swimming pools, residences, and the like. Some are now switching to renewable energy. A new supercomputing center in the Netherlands, for example, runs on wind power purchased from Norway. Last year Swinburne University of Technology in Melbourne, Australia, bought wind power to offset all of its energy use, including for its supercomputer.

In September 2020 CERN released its first public environment report; an update is scheduled to come out this fall. The initial report looked at emissions for 2017 and 2018. It says that in 2018, CERN produced 192 000 tons of CO_2 equivalent (tCO_2e). More than 90% of those direct emissions were related to Large Hadron Collider experiments. In particular, fluorinated gases used in particle detection and detector cooling were major greenhouse gas contributors. The lab's electricity consumption added 31 700 tCO_2e.

CERN has committed to a 28% reduction in its direct emissions by the end of 2024. It is focusing on fixing leaks, recuperating gas, and replacing fluorinated gases with more environmentally friendly gases.

The 39-meter Extremely Large Telescope, slated to receive first light at the end of the decade, will add to ESO's carbon footprint. Among the ways the organization is looking to trim its impact on climate are to optimize the number of people at its high-desert telescope sites and to hold more meetings remotely. Planned increases in the use of solar energy and reduced travel could cut emissions by 15%, says Arsenault. "We want to reduce our carbon footprint without hindering our science," he says. "It's a big change in mentality. It's difficult and it takes sacrifices."

Impacts on science

But doing nothing will also affect science. Faustine Cantalloube is an A4E member based at the Laboratory of Astrophysics of Marseille in France. She uses large telescopes to study exoplanets by direct imaging and has analyzed how climate change threatens observing.

The main threat is wildfires. "You can't see anything during a fire, and ashes can interfere with observing for weeks," Cantalloube says. "We know that because of climate change, fires are more powerful and last longer than they used to." Hurricanes and storms are additional threats. For example, climate models predict increasing numbers and severity of storms in Hawaii, one of the world's top observing sites. "Storms will affect the local population and how the observatories operate," she says. "Social stability, with access to resources such as food, water, and energy, is needed to run an observatory."

Rising temperatures are also a threat, says Cantalloube. Some instruments are built to operate within a specific temperature range, she explains, and if temperatures rise even a degree or two, they may have to be redesigned. Additional adjustments could be necessary to keep the temperature inside a telescope dome the same as outside to avoid turbulence when the dome is opened, she says. And the potential effects of changes in humidity that could come from climate are unclear: "Humidity is one of the most difficult things to predict. We don't have enough data yet."

Systemic change

"Climate change is already affecting every inhabited region across the globe with human influence contributing to many observed changes in weather and climate extremes," according to the IPCC's recent assessment. The report makes clear that the window for preventing catastrophic scenarios is closing and that the current decade is critical.

Often it's early-career researchers who are most vocal about countering climate change. That tendency can create a tension with career advancement, says Natasha Hurley-Walker, a radio astronomer at Curtin University in Perth, Australia. "You have to establish yourself in a system that has certain metrics," she says. Those metrics include the numbers of workshops hosted, conferences attended, grants won, papers published, students advised. "A big chunk of that is international visibility," she notes.

"We are all embedded in the system," says Hurley-Walker. "I can raise my voice. I can give talks about climate change. But I can't stop running supercomputing jobs—that would tank my career." And, she says, "it's added stress on junior researchers if their efforts to fight climate change are counter to the sentiments of those in leadership positions."

Hurley-Walker says that "colleagues who have chosen not to travel have not progressed as well in their careers." A Labos 1point5 study backs up her anecdotal observation: It found a statistically significant correlation between the number of flights taken by researchers and the number of papers they published. (Berné mentioned the study in a talk at last summer's European Astronomical Society meeting, see https://youtu.be/hcWRiwUNIEg.)

More thought should be given to who travels and to which conferences, says Adam Stevens, a computational astrophysicist at the University of Western Australia. Senior scientists travel much more than junior ones do, he notes. Yet early-career scientists are in greater need of visibility and opportunities to meet people. Even now, as a postdoc who supervises PhD students, he says, "I would send a student to a conference rather than go myself. I already have a network of collaborators."

What's needed are systemic changes, say members of A4E and Labos 1point5. Possible actions for institutions include limiting travel and compensating for their carbon emissions, employing more renewable energy, and tying purchases to suppliers' sustainability practices. Funding agencies could require applicants to include in their grant proposals pledges about climate change mitigation. "It's critical to focus on solutions," says San Francisco State University's Cool. "We can talk about causes and impacts, but we have to talk about solutions every time too. There are many solutions, and there is no silver bullet."

Joint efforts, such as an open letter originally published by A4E on its website this past April on Earth Day, take some of the pressure off individual researchers. That letter's signatories grew to include 2858 astronomers—and counting—from 81 countries. They call for astronomical institutions to name sustainability as a primary goal, adopt practices to lower carbon emissions, and communicate those goals widely.

"What's missing for the big transition to green energy and a more sustainable lifestyle is the emotion," says Leiden University's Burtscher. "It's worth changing our lives to keep living on this planet."

This past spring Labos 1point5 got funding from the CNRS and INRAE; that endorsement allows its members to do some of their work on climate change mitigation on the clock. And, Berné says, "bosses of CNRS labs and other institutions are asking Labos 1point5 for help and support in starting the transition to lower carbon emissions."

Incentives can change things, says Berné. "The biggest challenge is to convince politicians we have to do something and we have to do it now."

Toni Feder

Idaho project tests the limits of DOE aid to advanced reactors

The department says the Versatile Test Reactor is vital to the future of the US nuclear industry. Critics say it is duplicative and that industry should help pay for it.

IDAHO NATIONAL LABORATORY

A RENDERING of the proposed Versatile Test Reactor shows the reactor building (with logo) and surrounding experimental hall. The structures to the left are heat exchangers that would disperse heat from the liquid sodium coolant.

Does the US need a new multibillion-dollar test facility for developers of advanced nuclear reactors? Should those developers share the cost to build it? Could an advanced commercial reactor that's slated to be built with $2 billion in taxpayer funding be modified to also provide those testing capabilities?

Those questions have swirled around the Versatile Test Reactor (VTR) that the Department of Energy wants to build at its Idaho National Laboratory (INL). The project was imperiled in July after House and Senate appropriators stiffed DOE's request for $145 million in fiscal year 2022 funding. Then in September, the House Science, Space, and Technology Committee included $95 million for the VTR in its portion of the $3.5 trillion budget reconciliation package that President Biden and Democratic leaders were hoping to pass without Republican support. As Physics Today went to press, negotiations between the White House and House Democrats were expected to yield a much smaller spending package. If signed into law, funding would bypass the appropriations process and become available immediately. Senate Democrats hadn't released counterpart legislation.

The VTR snub by appropriators comes after DOE's Office of Nuclear Energy last year committed more than $5 billion over seven years to its Advanced Reactor Demonstration Program (ARDP), supporting 10 advanced-reactor projects. Each of those employ technologies having coolants other than light water, which is used by all US commercial reactors. The department last year also pledged another $1.3 billion to help finance what is expected to be the first commercial small modular reactor (SMR) deployed in the US (see Physics Today, December 2018, page 26).

The ARDP and SMR projects would

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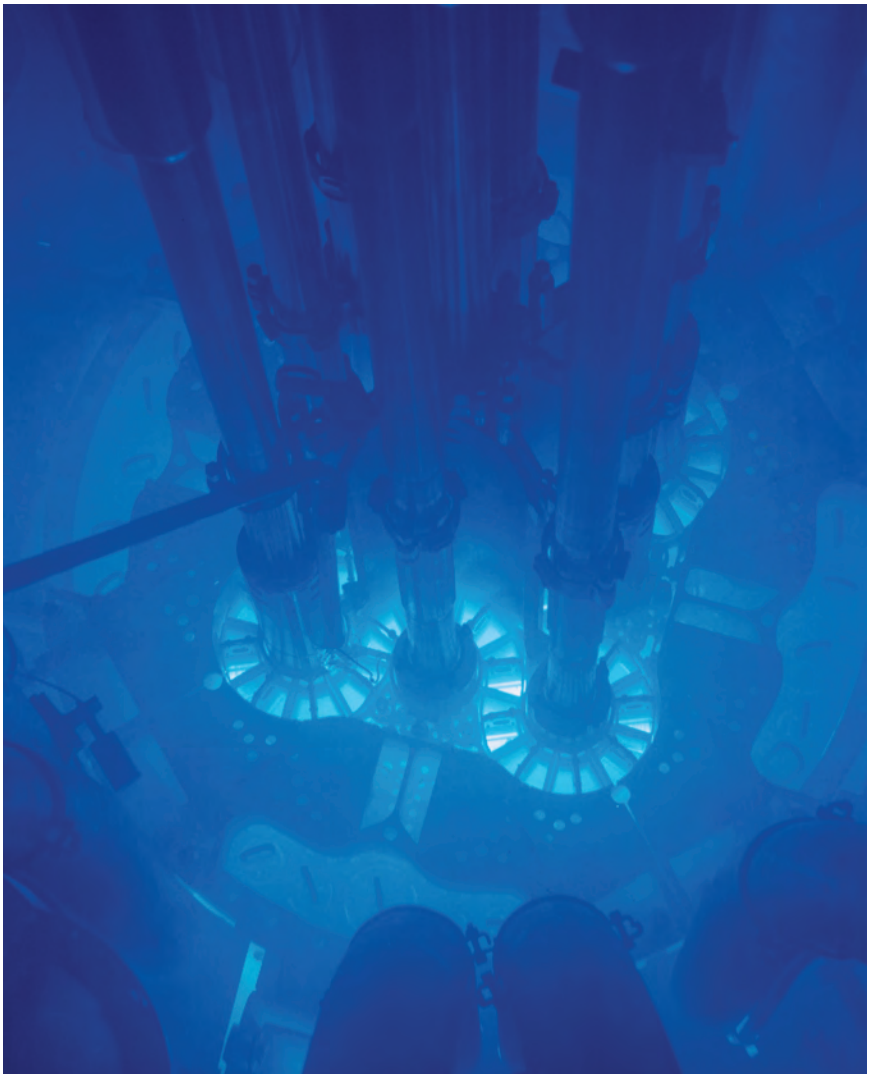


CHERENKOV RADIATION casts a blue glow in the core of Idaho National Laboratory's Advanced Test Reactor, the world's largest test reactor. As a light-water reactor, its usefulness to developers of advanced reactors is limited.

be fully funded under House and Senate spending bills. Industrial partners would share the cost of them to varying degrees. But DOE maintains that the VTR, as a user facility, should be wholly owned and financed by the government. That has long been the practice for other DOE test reactors, such as the Advanced Test Reactor (ATR) and the Transient Reactor Test Facility, and for the synchrotrons, neutron sources, and other scientific user facilities that the agency has built and operates.

Staff from the House and Senate Appropriations Committees didn't respond to several requests for comment. But the report accompanying the FY 2021 Senate version of the energy and water development appropriations bill expressed concern that DOE hadn't obtained commitments from the private sector or foreign governments "for monetary and in-kind contributions" to the VTR. The report instructed the agency to submit by late January a plan for converting the VTR into a public–private partnership. In a 7 October statement to PHYSICS TODAY, DOE said the plan was still under development and "will address collaborations with industry, such as the VTR/TerraPower [combination], as one of the methods the VTR will use to establish public–private partnerships to complete this critical piece of nuclear energy research and development infrastructure."

Congress hadn't completed action on FY 2022 appropriations as of press time, and federal funding was frozen at

FY 2021 levels under a continuing resolution that expires on 3 December. That extension will allow VTR design and preconstruction activities to proceed at last year's level of effort through the period. DOE plans to formally decide in 2027 whether to build the reactor. Construction is expected to take up to five years.

Look-alikes

Although the VTR would not produce electricity, it would resemble the Natrium, a commercial-scale sodium-cooled fast reactor (SFR) to be built by a partnership of the same name between TerraPower, GE Hitachi Nuclear Energy, and Bechtel. Natrium is one of the two large ARDP projects DOE selected last year to receive $2 billion each over seven years. The other recipient is X Energy, which is to build a four-module high-temperature gas-cooled reactor, the Xe-100. Appropriators okayed DOE's full FY 2022 requests of $133.6 million for the Natrium and $108.7 million for the Xe-100.

Natrium is not only building its eponymous SFR. Last year DOE selected it through a competitive process to design and build the VTR. But the Natrium SFR is scheduled for completion by 2028, years before the VTR could begin operating. The VTR would borrow many of Natrium's features, including electromagnetic pumps, intermediate heat exchangers, and sodium and gas cleanup systems, says Kemal Pasamehmetoglu, the VTR project's executive director at INL. "We are identifying the elements where development benefits both projects and trying not to do them twice," he says.

A memorandum of understanding signed in June by the lab manager, the Natrium partners, and Acting Assistant Secretary for the Office of Nuclear Energy Kathryn Huff characterizes the technology-sharing arrangement as a public–private partnership. But the agreement specifically excludes any cost sharing.

Pasamehmetoglu says he doesn't believe commercial developers would help pay for a user facility that would test potentially valuable technologies while being open to all industry players and to academic researchers. Who should decide who should contribute? he asks. "If one company comes in and helps us financially, does that mean that its competitors can't use the reactor? In my opinion, a test reactor is a government responsibility, just like the other test reactors we have had [at INL]."

As with other DOE user facilities, access to the VTR would be free if the results were made publicly available. The lab would charge for proprietary research. Academic researchers and developers of SFRs and other advanced-reactor types, such as lead cooled and molten salt, could try out new fuels, materials, and instruments and sensors in the VTR's high-flux and high-energy neutron environment.

In contrast to light-water reactors (LWRs), SFRs operate with unmoderated, high-energy neutrons. Proponents say that, compared with LWRs, such so-called fast reactors offer higher efficiencies, longer stretches between refuelings, and lower costs.

The Natrium SFR will operate initially with fast-reactor technology developed at INL's Experimental Breeder Reactor-II, an SFR that was shuttered in 1994, says Pasamehmetoglu. But the Natrium partners will benefit in the years ahead from improved fuels and materials to be developed at the VTR, he says.

"Natrium's long-term goal is to go to a very high burnup, long-lasting fuel."

A tenuous go-ahead

DOE gave a provisional green light to the VTR project in 2020, allowing INL to continue drafting a conceptual design and firming up cost estimates. Currently, the price tag is set in a broad range from $2.6 to $5.8 billion.

DOE solicited expressions of interest from industry for a VTR partnership in 2019. It received four responses in January 2020, including the TerraPower–GE Hitachi proposal. The other respondents, which Pasamehmetoglu declined to identify, "didn't match what was needed for the VTR," he says. "We were looking for someone who could design and build it."

The Natrium SFR and the VTR are to be fueled with metallic fuel. Natrium's will be high-assay low-enriched uranium (HALEU), which is enriched in the fissile ^{235}U isotope up to 20%. (Today's LWRs run on enrichment levels of around 4%.) The VTR's HALEU will be alloyed with plutonium to increase the neutron flux and to minimize reactor size, says Pasamehmetoglu.

DOE and reactor developers say the US's lack of a fast-neutron testing capability is slowing the testing of materials and fuels for all types of reactors, including the existing commercial fleet. But should taxpayers fund two nearly identical reactors? No, says Edwin Lyman, director of nuclear power safety at the Union of Concerned Scientists. Converting the Natrium SFR to serve as both a test and a demonstration reactor would save billions, he says. What's more, DOE-supported graduate students could begin their experiments on the Natrium SFR years sooner than they would if they had to wait for the VTR. Indeed, in 2016, GE Hitachi had proposed building an SFR that would combine testing and electricity-generation functions.

Pasamehmetoglu, however, says the missions of Natrium and the VTR are incompatible. Combining them will result in a less than optimum outcome in meeting the objectives of either mission. He notes that Russia, considered the US's main rival on fast reactors, recognizes the difference and is constructing a purpose-built test reactor.

In the absence of a US capability, the Bill Gates–founded TerraPower has resorted to Russia for some tests at Rosatom's BOR-60 fast reactor. Russia also happens to be the world's sole seller of HALEU. "Russia is happy to be a supplier and make money from it," says Seth Grae, CEO of Lightbridge, which is designing a HALEU fuel for US commercial reactors. DOE has made small amounts of HALEU available for R&D by diluting its excess highly enriched uranium.

The VTR won't be of much use to thermal-neutron high-temperature gas-cooled reactors such as X Energy's Xe-100. But it could help developers of fast-neutron HTGR designs. HTGRs use fuel that's encapsulated in tens of thousands of graphite-coated and high-heat-resistance pebbles.

Carl Perez, CEO of Elysium Industries, says he supports the VTR even though his company is planning to complete its own prototype molten-salt test reactor by 2028. "Having the government, its employees, and national lab employees work on building a reactor at a national lab will directly help Elysium when we go build a demonstration unit at a national lab," he says.

But the VTR could be of benefit to more than just nuclear energy, says Jeff Terry, a physicist at the Illinois Institute of Technology. Irradiation studies of materials that would require 10 years to perform at INL's ATR could be accomplished in three at the VTR, he says. Noting an application further afield, he says, "Some of my colleagues would like to use the VTR for antineutrino research." As for cost sharing, he notes, "At some point, it's the government's job to build tools we can use."

Today, the ATR is the world's most powerful test reactor. As an LWR, however, it is of limited value for advanced-reactor hopefuls, and it is largely reserved for the US Navy's nuclear propulsion reactor program. Though it's possible to boost the energy level of thermal neutrons, the ATR's neutron flux is an order of magnitude below the VTR's design specifications. Such high flux is necessary to accelerate the testing and shorten the development times for fuels and materials.

Still, developers of advanced reactors could meet some of their needs at the ATR if its capacity were increased, says Grae. "For about $30 million, we could triple the capacity [of the ATR] and be more competitive with Russia and China. We're not doing that, in part because these well-funded advanced-reactor projects are looking for billions, not tens of millions."

A full plate

Some observers believe that DOE's nuclear energy office simply has too much on its plate. "The fundamental question is whether there can be enough money in the DOE budget to pursue both the VTR and the ARDP effort at the same time," says Richard Meserve, a former chair of the Nuclear Regulatory Commission who cochairs DOE's Nuclear Energy Advisory Committee.

The ARDP also includes funding for five advanced-reactor ventures that the agency said could become commercial within 10–14 years. Those will share $1.2 billion over seven years to further their designs and support licensing activities.

Outside of the ARDP, DOE has committed $1.3 billion to the Carbon Free Power Project, an entity established by a consortium of utilities to build an SMR power plant at INL designed by NuScale Power. Originally proposed as 12 modules with a combined 720 MW of electric capacity, the project was scaled back in July to six units totaling 462 MW. The first module is slated to begin operating in 2029.

David Kramer PT

The Sculptor dwarf spheroidal galaxy. (Courtesy of the Dark Energy Survey.)

Josh Simon is an astronomer at the Carnegie Observatories in Pasadena, California. **Marla Geha** is a professor in the astronomy and physics departments at Yale University in New Haven, Connecticut.

Illuminating the DARKEST GALAXIES

Joshua D. Simon and Marla Geha

The behavior of extremely dim galaxies provides stringent constraints on the nature of dark matter. Establishing those constraints depends on precise stellar-motion measurements.

You might not think that galaxies and Hollywood celebrities have much in common. But like a true celebrity, our Milky Way is surrounded by a galactic entourage. We currently know of roughly 60 smaller galaxies in orbit around it, and an equal or greater number are thought to remain undiscovered. And like a good entourage, the satellites have a combined brightness that is less than the Milky Way itself by an order of magnitude. The smallest and most numerous of the satellites are known as ultrafaint dwarf galaxies, and both their number and their internal structures provide crucial information about the nature of dark matter.

Although we cannot directly observe dark matter, stellar motions in a galaxy are dictated by its gravitational potential and can reveal the dark matter's spatial distribution. Evidence of dark matter is observed in nearly all galaxies, but ultrafaint galaxies are the most extreme, with dark matter typically making up approximately 99.9% of their mass.[1] The meager 0.1% of ordinary matter is also exceptional—the majority of stars in ultrafaint dwarf galaxies were formed shortly after the Big Bang, making them unique probes of stellar nucleosynthesis (see the article by Anna Frebel and Timothy C. Beers, Physics Today, January 2018, page 30) and galaxy formation. Yet those valuable galaxies were unknown before 2005. It turns out they were hiding in plain sight.

Through most of the 20th century, searches for new dwarf galaxies around the Milky Way relied on visual examination of photographic plates. Surveys such as the Palomar Observatory Sky Survey and the European Southern

Observatory and Science Research Council's Southern Sky Survey imaged the entire sky using small telescopes equipped with the latest in photographic technology. At best, the hypersensitized glass plates used at observatories could record photons with about 3% efficiency. Nevertheless, a handful of dwarf galaxies were identified through careful inspection (by eye, with a magnifying glass!) of the survey images. By 2000 the known population of dwarf galaxies orbiting the Milky Way totaled 11 (see figure 1), none of which were ultrafaint. The brightest two, the Magellanic Clouds, have luminosities approximately a billion times that of the Sun and are visible to the naked eye in the southern sky. The faintest, in contrast, is the Sextans dwarf spheroidal. Discovered in 1990, it has a luminosity equivalent to that of just 300 000 suns.[2]

The invention of the CCD in 1969 enabled the era of modern astronomy. CCD detectors record nearly all incident photons and in minutes can reveal faint stars that remained invisible in hour-long exposures with photographic plates. Faster and more efficient detectors were developed throughout the 1980s and 1990s, and similar digital detectors are now in nearly all our pockets in the form of camera phones (see PHYSICS TODAY, December 2009, page 12). But it took time for semiconductor manufacturers to build sufficiently large devices to compete with photographic plates for imaging large areas—a square degree or more—of the sky.

Modern digital surveys began in the early 2000s with the Sloan Digital Sky Survey and continue with, among others, the Dark Energy Survey (see the article by Joshua Frieman, PHYSICS TODAY, April 2014, page 28). Digital imaging now covers almost the whole sky and records objects an order of magnitude dimmer than those found in the best photographic surveys. The images are captured electronically, so catalogs of the position, brightness, and color of every detected star or galaxy are generated automatically. Rather than poring over physical images to identify the fuzzy, tiny patch of a faint galaxy, astronomers can use computer algorithms to isolate groups of stars with the appropriate brightness and color to reside in a dwarf galaxy.

The digital surveys almost immediately revealed dwarf-galaxy candidates—groups of stars that appeared to be located at tens to hundreds of kiloparsecs from the Sun. The faintest of the newly discovered objects consist of merely 1000 stars, thus earning their "ultrafaint" moniker.

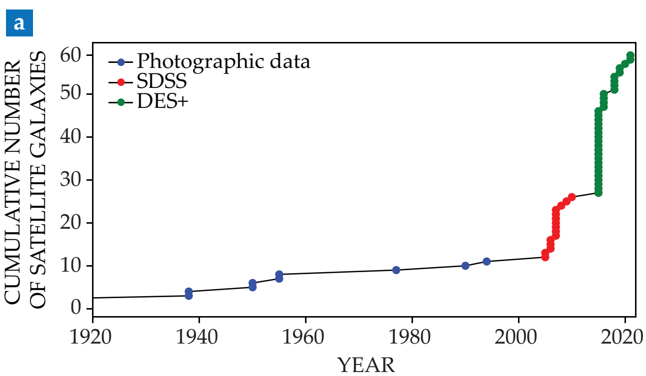
Images alone, however, cannot confirm that those objects are indeed galaxies. The stars must be gravitationally bound to each other rather than be a chance alignment of unrelated stars at different distances (see box 1). To establish the system's nature, its dynamical mass—the mass inferred from the motions of its stars—must be measured and compared with the total mass of the stars. If those values are equal, then the collection is considered a star cluster. But if the dynamical mass is much larger, it's a galaxy. Demonstrating that a candidate meets that criterion requires measuring the velocities of a substantial number of stars in each group.

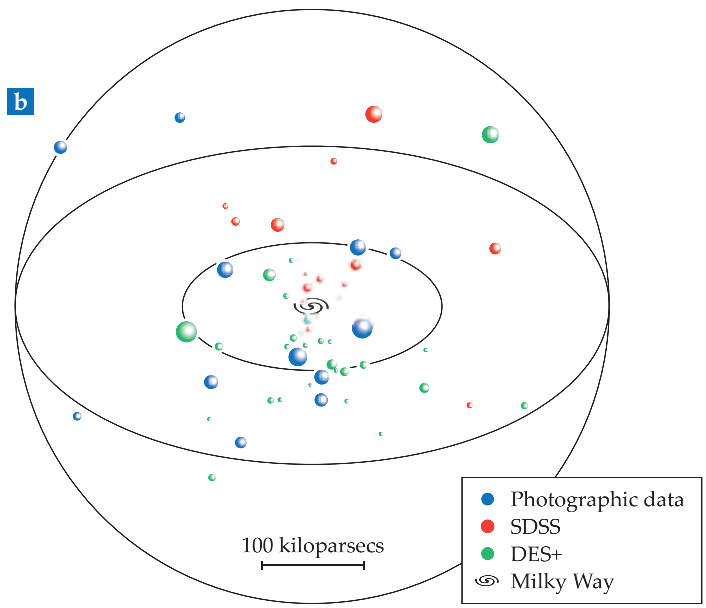
Are they really galaxies?

On a warm evening in February 2007, the two of us were on the island of Hawaii. We were preparing to use the 10-meter Keck II Telescope—along with Keck I, the two most powerful optical telescopes in the world—to measure the motions of stars in the first candidate dwarf galaxies discovered by CCD observations. Eight such objects had recently been published by Sloan Digital Sky Survey researchers.[3,4] If any candidates were indeed galaxies, they would be the first new Milky Way satellites discovered in more than a decade. Confirming all eight candidates would nearly double the known population of Milky Way satellites. Between us, we optimistically hoped that one or two of the candidates would turn out to be real. But just a few days before our scheduled telescope time, the weather forecast suggested that cloudy skies would ruin all three nights of our observing run.

We planned to use the telescope's Deep Extragalactic Imaging Multi-Object Spectrograph (DEIMOS) to obtain spectra of stars in the candidate galaxies. Stellar spectra contain dark absorption lines at fixed wavelengths, signatures of thermally generated photons from the hot stellar interior that are being absorbed by the star's cooler photosphere. By measuring the

FIGURE 1. SATELLITE GALAXIES are easier to discover since the advent of digital sky surveys. **(a)** Before 2000, only 11 were found, largely by scouring photographic plates. The Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey and others (DES+) are responsible for increasing that number to more than 60. **(b)** The spatial distribution of satellite galaxies around the Milky Way.





shift in those lines from their expected rest wavelengths—their Doppler shifts—we can determine the line-of-sight, or radial, velocity of the star.

The accuracy of a radial-velocity measurement is set by the accuracy to which the centers of the absorption lines can be determined. Higher-resolution spectrographs and longer exposure times can both generate more accurate radial velocities. DEIMOS can obtain simultaneous spectra for nearly 200 stars with an accuracy of 2 km/s. Stars in any given dwarf galaxy share approximately the same radial velocity, with a variation of 5–10 km/s (see figure 2). Stars that do not belong to the dwarf galaxy, typically foreground stars residing in the Milky Way, can span a wide range of velocities (about 100 km/s). Thus DEIMOS has sufficient resolution to determine whether a star is gravitationally bound to one of the Milky Way's dwarf galaxies or is instead part of the Milky Way itself.

The same stellar-velocity data can also be used to determine the mass of a dwarf galaxy. Once a sample of stars is identified as belonging to a dwarf galaxy, the galaxy's total mass can be computed from the velocity dispersion (the width of the velocity distribution) using Newton's law of gravitation. Although the first dwarf-galaxy velocity-dispersion estimates, obtained in the 1980s by Marc Aaronson[5] and others, relied on single-digit numbers of stars, the minimum number of member stars needed to confirm a dwarf-galaxy candidate is usually larger than 10. Improvements in telescopes, spectrographs, and detector technology have now made it possible to measure velocities for up to a few thousand stars in the largest dwarfs. The resulting mass and density determinations are crucial for dark-matter experiments.

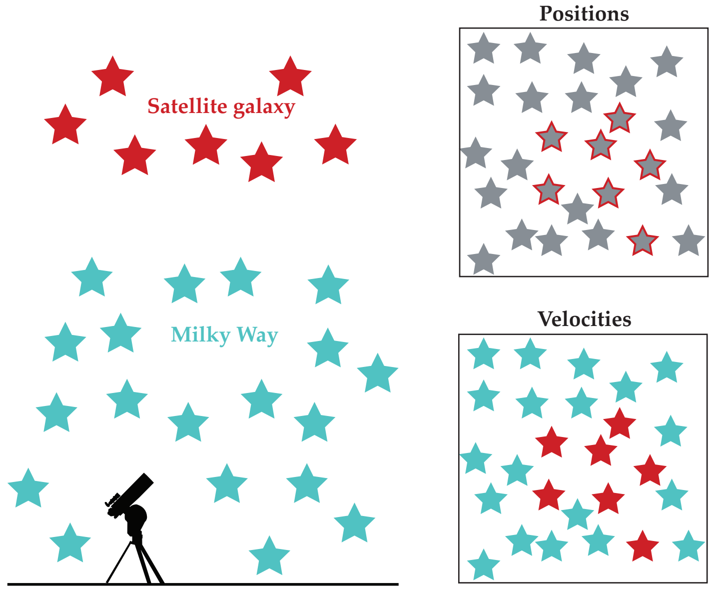


FIGURE 2. A SATELLITE GALAXY imaged by an Earth- or space-based telescope, as illustrated on the left, captures only the stars' positions. That information (top right) is insufficient to definitively determine which stars in the field of view are part of the satellite galaxy. But the satellite is moving relative to the Milky Way, where the observer is located. When velocity data are taken into account (bottom right), the stars become distinguishable as distinct populations.

On the eve of our 2007 Keck observing run, the weather made a welcome turnaround. During our three nights, we measured radial velocities for more than 1000 stars and confirmed that all eight of the candidates we targeted were in fact dwarf galaxies. Since then, more than 35 similar systems have also been confirmed by stellar spectroscopy.[6]

Remarkably, our observations also suggested that the total masses of those faint galaxies were overwhelmingly dominated by dark matter rather than their visible stars. The known Milky Way dwarf galaxies already shared that property, but the ultrafaint dwarf galaxies are more extreme, with visible stars accounting for well under 1% of the total mass. The ultrafaint systems therefore provide excellent laboratories for testing theories of dark matter. Below we describe three tests: the overall number of dwarf galaxies around the Milky Way, the amount of dark-matter annihilation radiation from each galaxy, and the galaxies' internal density structures. Each test provides unique information about dark matter.

Counting dark-matter halos

The prevailing cosmological model, developed over the past 40 years, is based on the concept of cold dark matter (CDM). In that context, "cold" refers to the typical velocity of dark-matter particles—they would have been nonrelativistic when they decoupled from baryons in the early universe. More recently, the discovery of dark energy has motivated the ΛCDM model, which includes both CDM and a dominant cosmological-constant term (Λ). The cosmological constant accounts for the acceleration in the expansion rate of the universe (see Physics Today, December 2011, page 14), but it does not affect dynamics at the scale of individual galaxies.

Theoretical investigations of the astrophysical behavior of dark matter employ large computer simulations of the evolution of structure in the universe and the galaxies within it. Those simulations take two forms: simulations with only dark matter moving under the influence of gravity and hydrodynamical simulations, which add baryonic physics such as radiation, star formation, and supernova explosions. Because of lower computational demands, simulations with only dark matter can reach higher resolution than hydrodynamical simulations, which have just recently begun to produce galaxies that closely resemble real galaxies. In both cases, the results can be compared with observations to evaluate whether the physics assumed in the simulations is correct.

Gravitationally bound concentrations of dark matter are referred to as halos, although as with much astronomical terminology, the name is misleading because dark-matter halos have high central mass densities and lower densities in their outskirts. If dark matter is cold, one prominent prediction from simulations is that large dark-matter halos should be surrounded by enormous numbers of smaller halos. The population of dark-matter halos follows a characteristic distribution in mass,[7] known as the mass function, in which the number of satellite dark-matter halos N scales with the mass of the host galaxy M as $dN/dM \sim M^{-1.9}$.

According to the mass function, a massive galaxy like the Milky Way should be accompanied by many smaller dark-matter halos. But hydrodynamical simulations suggest that only the halos with masses above about 10^8 solar masses ($M_\odot$)—four orders of magnitude smaller than the Milky Way's dark-matter halo—can form stars. Although halos below that limit may be detectable via gravitational lensing or their dynamical effects on thin streams of stars orbiting the Milky Way, most recent efforts to constrain dark-matter properties focus on the smallest concentrations with visible counterparts: dwarf galaxies.

Using the mass function to compare the observed dwarf-galaxy population around the Milky Way with theoretical expectations provides some of the strongest constraints on dark matter. The first such comparisons in the late 1990s and early 2000s revealed a major discrepancy: The number of dwarf galaxies around the Milky Way (11 as of 2005) was more than an order of magnitude short of the ΛCDM expectation.[8] In an excellent example of scientific branding, the mismatch was labeled the "missing satellite problem," and it provided significant motivation for considering alternative models of dark matter, including warm dark matter and fuzzy dark matter (see box 2). It now appears that the problem lay with the observational searches for dwarf galaxies.

Since 2005 the rapid progress of digital surveys in covering the sky has increased the total number of observed dwarfs orbiting the Milky Way to nearly 60, but all regions of the sky have not been searched with the same sensitivity. When that incompleteness is accounted for, the observed number of dwarf galaxies places strict limits on dark-matter-particle properties. Dark-matter models in which the predicted number of dark-matter halos is smaller than the observed number of dwarfs can be ruled out. Warm dark matter and self-interacting dark-matter models produce fewer dark-matter halos at $10^8\ M_\odot$, and therefore fewer dwarf galaxies, than CDM. With the latest dwarf-galaxy mass measurements, state-of-the-art theoretical models exclude warm dark-matter particles with masses below 6.5 KeV. The measurements also place strong constraints on other theories of dark matter.[9]

Future surveys, including with the Vera C. Rubin Observatory, scheduled for first light in 2023, are expected to approximately double the current Milky Way dwarf-galaxy satellite population over the coming decade. As of now, the population appears to be consistent with ΛCDM predictions[10] down to about $10^8\ M_\odot$. Mass measurements for the dozens of dwarfs Rubin will likely discover will make the test more sensitive, thereby strengthening limits on non-CDM dark-matter scenarios, such as fuzzy dark matter and dark matter that can interact with standard model particles.[11]

Light from dark matter

CDM particles are not expected to interact with baryons, but they may occasionally interact with each other. In currently favored models, dark-matter particles have masses above 1 GeV and can collide and annihilate into familiar standard-model species. The large particle mass means that the annihilations would produce high-energy photons, typically at gamma-ray wavelengths. Searches for that gamma radiation are called indirect-detection experiments because they seek particles originating from dark matter rather than dark matter itself.

The rate of dark-matter annihilation is proportional to the dark matter's density squared. Thus the brightest sources of annihilation radiation will be the nearest and densest concentrations of dark matter. The prime indirect-detection target is the Milky Way's center,[12] which is just 25 000 light-years away. Frustratingly, though, the galactic center also hosts every other known astrophysical source of gamma rays, including supernova remnants, pulsars, and occasional accretion onto the Milky Way's central black hole.

The next-best locations to look for dark-matter annihilation are the Milky Way's dwarf galaxies. They are relatively nearby and are free of any known sources of gamma rays, making them remarkably clean targets for detecting high-energy radiation from annihilating dark-matter particles. As with other dark-matter tests, stellar spectroscopy is critical—velocity-dispersion measure-

BOX 1. STAR CLUSTER OR GALAXY?

Astronomers classify gravitationally bound systems containing stars into two categories: galaxies and star clusters. Both can include either young or old stars, but galaxies encompass a broader range of masses, sizes, and morphologies. The fundamental difference between the two is thought to relate to their dark-matter content. Galaxies, such as Leo IV (left image), form in deep gravitational potential wells established by concentrations of dark matter and contain at least five times as much dark matter as ordinary matter. Clusters, such as Palomar 12 (right image), arise from unusually dense gas clouds and do not contain detectable amounts of dark matter. Despite having a similar luminosity to Palomar 12, Leo IV is invisible in the image below because the surface density of its stars is smaller by a factor of 100.

Before the discovery of ultrafaint dwarf galaxies, the two classes could be separated using the classic Potter Stewart aphorism "I know it when I see it." Yet as increasingly faint dwarf-galaxy candidates were identified, the properties of star clusters and the new galaxies overlapped. A more rigorous definition was needed. In 2012 Beth Willman and Jay Strader proposed the following: "A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity."[18] Their definition avoids specifically referring to dark matter, as its existence has not yet been confirmed, and enables a stellar system to be classified by comparing its dynamical mass with the mass of its stars.

Ultrafaint dwarf galaxy


NASA/ESA/T. BROWN/STSCI

Star cluster


NASA/ESA/HUBBLE SPACE TELESCOPE

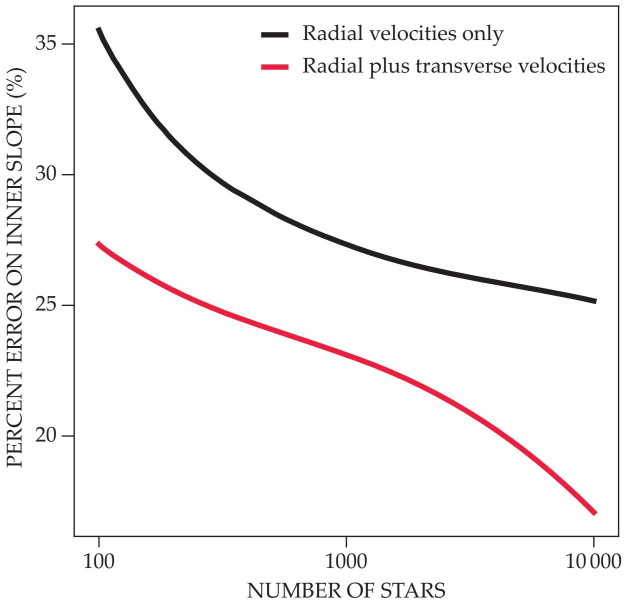


FIGURE 3. THE PRECISION to which a galaxy's mass density profile can be determined depends on the number of observed stars. Here, the estimated error in the key property of the density profile—its inner power-law slope—is plotted as a function of the number of stars observed. The black curve assumes that only radial-velocity measurements are available for each star. The red curve assumes that both radial- and transverse-velocity measurements are available. Errors of 2 km/s are assumed on individual radial-velocity measurements, whereas 5 km/s is assumed for transverse velocities. An inner-slope measurement with a certainty of 4–5 standard deviations can only be obtained with three-dimensional velocity measurements. (Courtesy of Juan Guerra, Yale University.)

ments determine the central dark-matter density, and hence the expected annihilation rate, in each dwarf. Multiple gamma-ray telescopes are searching for annihilation radiation from the Milky Way's satellite galaxies. Although they have yet to convincingly detect dwarf-galaxy gamma-ray emission, their nondetections place the most stringent limits to date on the dark-matter particle's interaction cross section. Specific limits depend on the dark-matter model and annihilation channel being considered, but the experimental sensitivity has reached the theoretically expected cross sections[13] for dark-matter masses lighter than about 100 GeV.

Gamma-ray observations of the Milky Way's dwarf galaxies, especially the numerous and nearest ultrafaint dwarfs, may hold the key to understanding the nature of dark matter. Further improvements to dwarf-galaxy density estimates and more sensitive gamma-ray observations will provide progressively stricter constraints on, and perhaps even a detection of, the elusive matter.

Cusps versus cores

The third constraint on the nature of dark matter provided by the Milky Way's dwarf galaxies comes from measuring their internal mass distributions. Simulations consistently predict[14] that dark-matter halos consisting of CDM particles have central density distributions where the density ρ as a function of radius r approximately follows $\rho(r) \propto r^{-1}$. Such a dark-matter profile is referred to as "cuspy." Dark-matter particles with larger self-interaction cross sections or smaller masses—as used in warm-dark-matter models—generally lead to less-dense central regions. In those cases, the inner density profile either increases more gradually toward the center or is independent of radius. The flatter density profiles are called "cores."

Observations of dark-matter density profiles in bright dwarf galaxies—with masses of 10^{10}–10^{11} $M_\odot$—beyond the Milky Way suggest that dark matter is not as centrally concentrated as predicted by ΛCDM. That is, the central dark-matter densities are often core-like and do not increase as rapidly as r^{-1}. That discrepancy is known as the "cusp–core problem,"[15] and it could be a signal that dark matter is not cold or that dark-matter particles have a significant interaction cross section.

It has become clear over the past decade, however, that massive dwarf galaxies are not the pristine dark-matter laboratories that astronomers once thought them to be. Their baryon fractions can be as high as about 50% in their central regions. Hydrodynamical simulations of galaxy formation have revealed that when many supernova explosions occur close together in time, enormous quantities of gas are first blown out of the galaxy and later recondense, producing strong fluctuations in the gravitational potential.[16] Even if the dark matter does not directly couple to the baryons, it must respond gravitationally by spreading out and reducing the central dark-matter density.

Those simulation results have intensified interest in galaxies containing fewer stars because those galaxies never host enough supernovae to experience such dark-matter rearrangement. By measuring the central dark-matter distribution in those truly dark-matter-dominated systems, researchers hope to determine whether the density profiles of pure dark-matter halos support the ΛCDM paradigm.

Unfortunately, radial velocities from stellar spectroscopy alone have proven to be insufficient to determine dark-matter density profiles of the Milky Way's dwarf galaxies. Analyses by separate groups over the past decade have favored cored profiles, central cusps, and everything in between. Even when relying on the same stellar data sets, independent teams have been unable to converge on a consistent answer.

The fundamental challenge is that stars orbit in three dimensions around the galaxy in which they reside, but radial velocities constrain only one of the three. Astronomers often make assumptions about the missing two dimensions, such as presuming that the stellar motions are isotropic. But the lack of three-dimensional velocity information leads to a degeneracy between the mass distribution and the stellar orbits. To directly determine each star's orbit—which would be a real breakthrough—radial velocities must be combined with velocities along the other two dimensions of the stars' motions.

Future observations in 3D

Although stellar motions are inherently 3D, for astronomical purposes it is convenient to divide them into two categories: radial motion along the line of sight and proper motion in the plane of the sky. Radial velocities are obtained from stellar spectroscopy, as described above, whereas proper motions are measured by determining the angular position of a star as a function of time. The ability to test dark-matter models by studying dwarf galaxies is limited by the number of stars that can be observed in each galaxy and the accuracy with which the individual stars' motions can be measured (see figure 3).

BOX 2. DARK-MATTER MODELS

Astrophysicists concluded decades ago that cold dark matter (CDM) best describes the universe. That conclusion was based on comparisons between the observed large-scale distribution of galaxies and numerical simulations of nonlinear gravitational clustering. Yet a particle with the expected CDM properties has failed to materialize in either collider experiments or sensitive underground searches, so theorists have more recently begun to seriously consider other ideas for the nature of dark matter.

In warm-dark-matter models, the particle—perhaps a fourth type of neutrino—has a much smaller mass and moves at significantly higher velocities than putative CDM particles. Such a particle would preclude structure on small scales, so a universe dominated by warm dark matter would contain fewer of the smallest dwarf galaxies.

Another prominent alternative dark-matter scenario is self-interacting dark matter, in which the particles interact often with one another. That interaction could be an analogue of electromagnetic interactions among ordinary matter. As with warm dark matter, the interactions would reduce the number of dwarf galaxies and potentially decrease the dark-matter density at the centers of galaxies.

Fuzzy, or ultralight, dark matter has recently garnered increased interest. In that model, the particles have such small masses (10^{-22}–10^{-19} eV) that their de Broglie wavelengths are approximately 1 kiloparsec, which is comparable to the sizes of galaxies and would lead to quantum interference effects on galactic scales.

The detailed implications of the alternative models are still being explored, but prospects for conclusive astrophysical tests in the foreseeable future appear promising.

Currently only the radial velocities of stars in the Milky Way's satellite galaxies can be measured with enough accuracy to test dark-matter models. In bright dwarf galaxies, like those discovered in older photographic surveys, several thousand stars are easily observable with existing telescopes. That is sufficient to determine the stellar velocity dispersion in the galaxy. On the other hand, the most recently discovered ultrafaint galaxies have as few as 5–10 stars bright enough for radial-velocity measurements.

Several new survey instruments that are either in the planning process or beginning operations will include spectrographs that can obtain data for thousands of stars at a time. Those tools, such as the Prime Focus Spectrograph on the 8.2 m Subaru Telescope in Hawaii and the Dark Energy Spectroscopic Instrument on the 4 m Mayall Telescope in Arizona, may produce larger gains for bright dwarfs than for faint ones. Larger future telescopes may bring more of the stars in ultrafaint dwarfs within reach and allow astronomers to measure radial velocities for perhaps hundreds of stars in those systems. Those facilities will be crucial for studying the ultrafaint dwarfs expected to be discovered in the coming years by the Rubin Observatory.

Much as the past 30 years have seen significant improvements in the ability to measure stellar radial velocities, the next 10 years will likely see similar advances to proper-motion measurements. Distant stars' proper motions are determined by comparing their positions with those of stationary background sources in images taken at least a few years apart. Even over decades, stars' transverse motions are extraordinarily tiny—akin to watching human hair grow from the Moon. Still, the *Gaia* satellite, launched by the European Space Agency in 2013, has now measured transverse motions for a remarkable 1.8 billion stars in the Milky Way and small samples of stars in its satellite dwarf galaxies.[17]

Although transverse-velocity measurements represent a phenomenal technical achievement, those acquired so far in the Milky Way's dwarf galaxies remain less than one-tenth as precise as currently available radial velocities and thus do not yet sufficiently constrain the dark-matter distribution. Anticipated ground- and space-based improvements are likely to change that situation in the foreseeable future. The European Space Agency recently released a highly anticipated third data set from *Gaia* that improves the proper-motion precision for individual dwarf-galaxy stars by a factor of two to three, and substantial gains are expected in the next few years. Further in the future, existing *Hubble Space Telescope* images of dwarfs will be combined with observations by the next generation of large telescopes. The exquisite angular resolution of those combined data sets will enable proper-motion measurements for hundreds of dwarf-galaxy stars with velocity errors comparable to current radial-velocity errors.

Determining the dark-matter distribution in dwarf galaxies with sufficient precision to meaningfully test theories of dark matter will ultimately require a combined analysis that features both radial and transverse stellar motions. The full 3D orbits for the observed stars in a dwarf galaxy will reveal the galaxy's underlying gravitational potential, thereby confirming or refuting the ΛCDM prediction of a cuspy dark-matter density profile and improving constraints on dark-matter annihilation rates. In that way, measurements of infinitesimal motions in seemingly insignificant galaxies may hold the key to determining the nature of dark matter throughout the universe. If so, the Milky Way's entourage may earn its own starring role.

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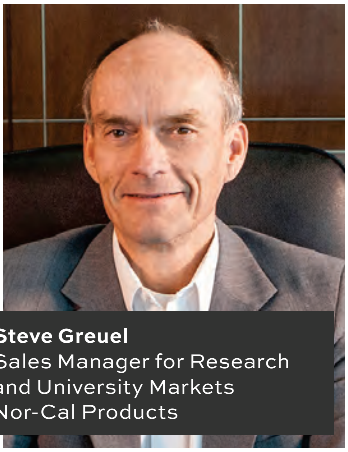
Nor-Cal Products' Custom Chamber Houses Ion Acceleration Experiments at BELLA



Steve Greuel
Sales Manager for Research and University Markets
Nor-Cal Products

Nor-Cal Products got its start in the 1950s when it began manufacturing parts for pumping stations used in the dairy business. After incorporating in 1962, the business shifted its focus to the emerging vacuum science industry. Knowledgeable in the forming, welding, machining, and cleaning of stainless steel, Nor-Cal Products quickly became the premier supplier of flanges, fittings, and custom components for industrial equipment manufacturers, universities, and national laboratories.

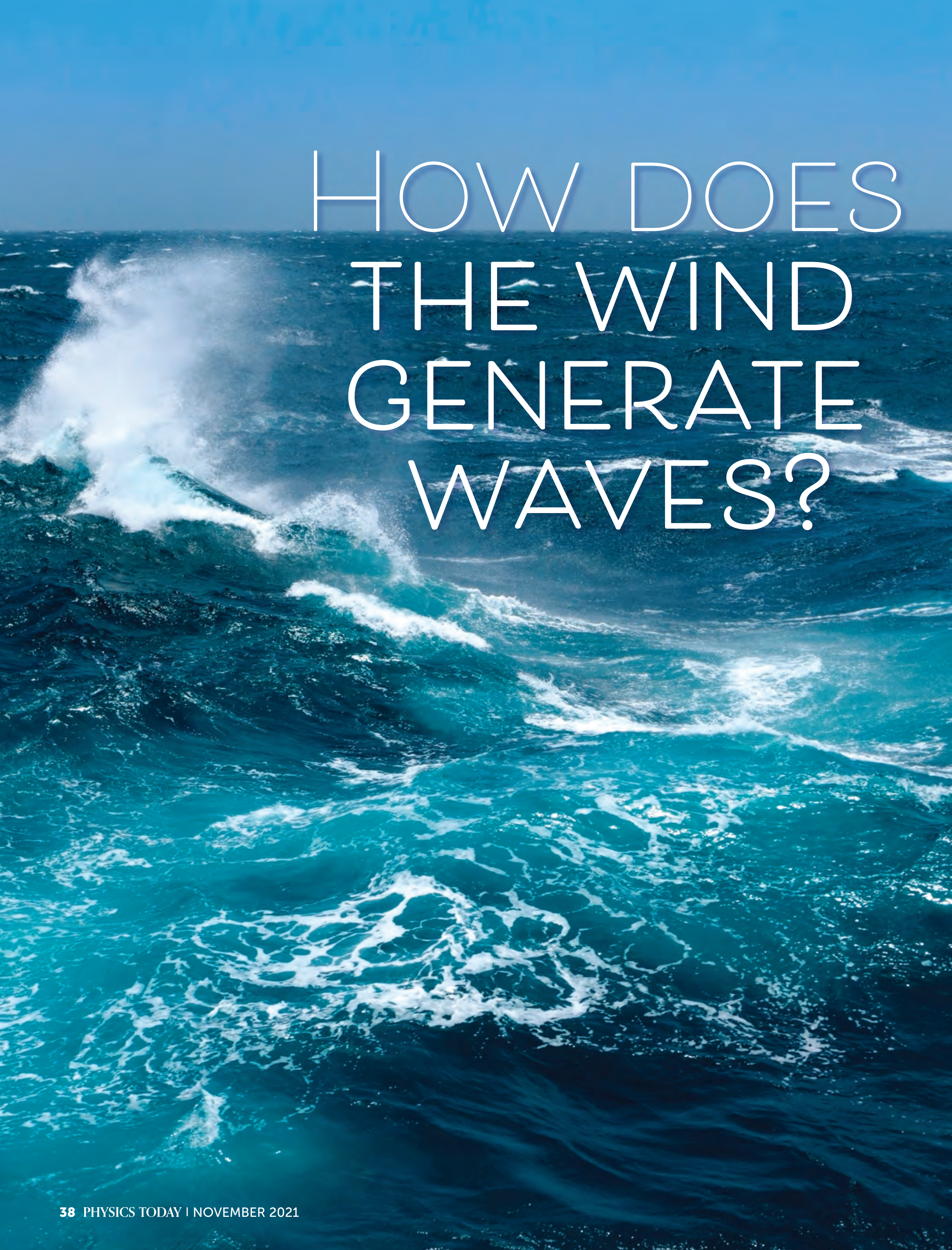
In 2017 Nor-Cal Products was acquired by the Pfeiffer Vacuum Group, another company at the forefront of the vacuum science industry. Today Nor-Cal Products benefits from the strength of Pfeiffer Vacuum as a leading global supplier, with its broader product portfolio, new technology solutions, and extensive sales network. Pfeiffer Vacuum benefits from Nor-Cal Products' manufacturing expertise, exceptional customer support, and reputation for unparalleled quality and integrity. The pursuit of advances in vacuum science has inspired both companies to excel in service to industry and research.

Nor-Cal Products serves many of the industry's largest markets, including specialty coatings and semiconductors. Among Nor-Cal Products' partners in research and development is the Lawrence Berkeley National Laboratory. Located within LBNL is the renowned Berkeley Lab Laser Accelerator, also known as BELLA. Overseeing Nor-Cal Products' relationship with LBNL/BELLA is Steve Greuel, Nor-Cal's sales manager and technical liaison for university and research markets. Since 2011 Steve has collaborated with the engineering group at LBNL, which uses precision manufacturing to bring to life new and specially designed nonmagnetic aluminum compressor and target chambers. Propelling those designs from paper into reality made Steve—and Nor-Cal Products—an integral part of readying installation at the BELLA facility.

Nor-Cal Products' most recent collaboration with LBNL saw the manufacture of an impressive vacuum chamber, octagonal in design and constructed of aluminum, that will house experiments at BELLA. Inside, a 500-mm-focal-length parabolic mirror will focus the 20-cm-diameter laser beam down to a laser spot of a few micrometers. Confining the 40-joule, 35-femtosecond laser pulse to such a small spot will result in intensities exceeding 1×10^{21} W/cm^2. Only a few experimental setups in the world reach such enormous intensities. Experiments will be directed primarily at ion acceleration from a thin target foil positioned into the laser focus. At BELLA, such laser-accelerated ion beams have been used to irradiate biological cell samples to explore new approaches for cancer therapy.

For customers like LBNL and many others in the vacuum-based research market, Nor-Cal Products remains a premier global source for innovative engineering, precision manufacturing, and exceptional service and support. Visit us at www.n-c.com.

How does the wind generate waves?



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Nick Pizzo, Luc Deike, and Alex Ayet

Although the question is a classical problem, the details of how wind transfers energy to waves at the ocean surface remain elusive.

To the modern Earth scientist, ocean waves are important because they influence the physics of the air–sea interface (see the article by David Richter and Fabrice Veron, PHYSICS TODAY, November 2016, page 34). The waves transport mass, and that wave-induced drift alters the dynamics of the upper ocean: It mixes the surface layers of water and modulates their temperatures, a crucial boundary condition between the air and sea in coupled models of Earth's weather and climate. More practically, statistical wave models describe how waves evolve and propagate across the ocean surface in various environmental conditions—such as low and high winds—and quantify how they influence the ocean's circulation and the transport of jetsam, flotsam, and pollution on its surface.

That wind produces waves in water is obvious to even the most casual observers. It has received attention for centuries from mathematicians and physicists. Even so, a complete description of the phenomenon eludes modern researchers. The difficulty comes from the fact that wave generation occurs at the interface of two fluids (here, air and water), with the flow in both generally turbulent. The waves vary sufficiently in space and time to be considered random, and the fluids interact over a broad range of scales—from millimeters to kilometers in space, and from seconds to hours in time. That range makes analytical and numerical progress extremely difficult.

The challenge in laboratory studies is to resolve the turbulent flow of air and water simultaneously over that large range on a curved and quickly changing surface. Field studies suffer from the difficulties of making measurements at sea, particularly when wind measurements are disturbed by the distortion produced by the presence of a research vessel. Despite those obstacles, much progress has been made experimentally—figure 1 shows a research platform at sea that avoids a research vessel's usual flow distortion—and theoretically to understand the phenomenon. In this article, we outline the problem, review historical approaches to solve it, and discuss some of the open questions.

Outline of the problem

Consider a horizontal wind blowing over a quiescent ocean. Under what conditions do surface waves form? The restoring forces for ocean waves are gravity and surface tension. The dynamics of the interface between the air and sea are governed by the requirements that stress is continuous and momentum is conserved in both fluids. That system is described by the Navier–Stokes equations. For small waves, and a fluid that contains no vorticity, it's linear and behaves like a simple harmonic oscillator, with evanescent waves propagating in the horizontal direction according to a dispersion relation.

But the system becomes deceptively complicated when waves are no longer linear, or when the flow in the air or water contains vorticity. Even worse, the boundary conditions must be evaluated at the rapidly varying wave interface, which itself is a dependent variable of the system. That adds significant complexity to the problem. Solving it requires using the nonlinear

Navier–Stokes equations at all points in the air–sea boundary and over the broad range of scales.

A statistical approach

Statistical wave models are one of the biggest drivers of research in the field, and they are of tremendous practical value to mariners, national security operations, and surfers alike. The models are based on the statistics of wave heights. The quantity known as wave action, which takes into account the effects of current on the waves, is the fundamental conserved quantity.[1] A pendulum with a varying string length is a direct analogue of waves in a current. When the length of the pendulum changes, so does the energy of the system. Similarly, water waves exchange energy with the currents, but the wave action remains conserved, which makes it the central feature in statistical wave models.

Modern statistical models are based on the evolution of the wave action spectrum and take the form

$$\frac{\partial N}{\partial t} + (\mathbf{c}_g + \mathbf{U}) \cdot \nabla N = S,$$

where N refers to the wave-action density—the wavenumber energy spectrum divided by the wave's intrinsic frequency $\omega = \sqrt{(g|k|)}$. The group velocity $\mathbf{c}_g$ equals $\partial\sqrt{(g|k|)}/\partial k$, in which g is the acceleration of gravity, k is the wavenumber, and $\mathbf{U}$ is the ocean current at the surface. Note that deep water waves are dispersive, so longer waves are faster than shorter waves.

The source term S in the equation refers to the sum $S_{in} + S_{diss} + S_{nl}$, in which S_{in} is the wind's input to the waves, S_{diss} is the dissipation of action primarily due to wave breaking, and S_{nl} is the nonlinear transfer of action through wave–wave interactions. The dot product term on the left-hand side of the equation represents the transport of wave action along the ocean's surface.

The nonlinear interactions S_{nl} were explained in the 1960s by Klaus Hasselmann and Vladimir Zakharov.[2,3] For surface gravity waves, they arise when four waves resonantly interact. That discovery, together with its implications for the existence of direct and inverse cascades in the water-wave system, earned Zakharov the Dirac Medal in 2003. (Hasselmann, incidentally, received the 2021 Nobel Prize in Physics for work he did on climate modeling.) A towering figure in the development of water-wave theory, Zakharov shared the medal with Robert Kraichnan, one of Albert Einstein's last postdocs, who elucidated analogous properties of two-dimensional turbulence. The behavior of the dissipation term S_{diss} is primarily controlled by wave breaking and remains an active area of research. In this article, we focus on the physics that leads to a better understanding of the wind's contribution to the waves' energy, S_{in}.

Wind-generation mechanisms in history

Many cultures have an intuitive understanding of the relationship between wind and waves. Micronesians and Polynesians, for instance, are famous for using swell to aid in their navigation.[4] The modern treatment of the relationship began with two pivotal figures of 19th-century physics, Hermann von Helmholtz and William Thomson (later Lord Kelvin), who argued that wind generates waves through a shear-flow instability. The two scientists would often discuss the issue on trips out on Kelvin's boat.[5]

FIGURE 1. A FLOATING RESEARCH PLATFORM known as R/P *FLIP*. The 355-ft vessel is used by scientists at Scripps Institution of Oceanography. It is towed horizontally to its position at sea and then flipped 90°, leaving 300 ft of the platform underwater and the part floating above uniquely stable and resistant to the waves that *FLIP* measures. The platform is equipped with instruments for research in geophysics, meteorology, and oceanography. The orange boom on the left side of the photo, for instance, has five anemometers mounted at various heights to measure changes in wind speed. (Courtesy of Laurent Grare, University of California, San Diego.)

The process, known as the Kelvin–Helmholtz instability, occurs whenever a fluid changes speed across a region of changing density. The pair calculated that for the mechanism to operate in realistic conditions, wind speeds of 6.5 m/s were needed to generate waves. But several laboratory experiments have since recorded wave generation at much lower wind speeds. Apparently, there is more to the story than what Kelvin and Helmholtz had proposed.

In 1925 Sir Harold Jeffreys argued that air flowing over water waves is, like air flowing past a sphere, deflected by surface geometry.[6] The analogy led to an understanding of what's now known as airflow separation—a reversal in the direction of airflow over the leeward side of a wave crest (see figure 2). The geometric phenomenon, which Jeffreys called sheltering, arises from a pressure difference between the windward and leeward sides of the wave. The wind pressure and slope of the water wave are both oscillatory, and when the two are phase-shifted with respect to each other, work is done on the wave, which causes it to grow. The theory has an unconstrained scaling parameter, known as the sheltering coefficient, that estimates the work done on the waves by the wind. Preliminary laboratory experiments of wind over solid objects showed that the sheltering coefficient depends crucially on the specific geometry of the object, which the Jeffreys theory does not account for.

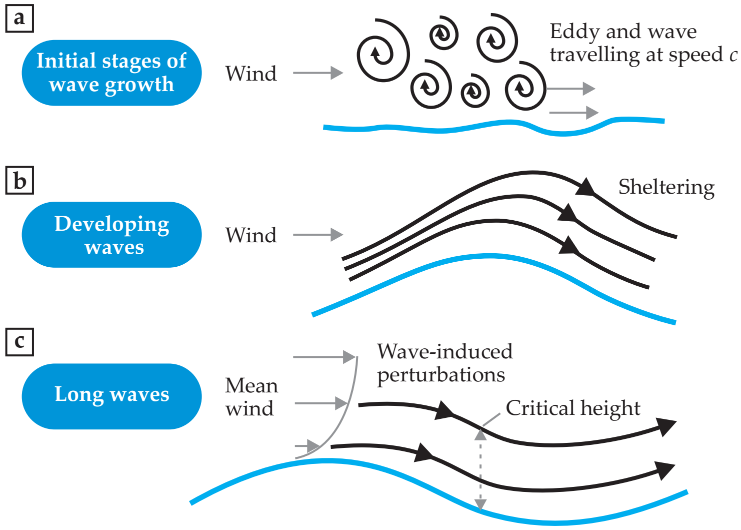

FIGURE 2. WAVE-GENERATION mechanisms. **(a)** Turbulent eddies in the air disturb an initially calm ocean and create ripples with wavelengths on the scale of centimeters. **(b)** Those ripples grow to meter-scale wavelengths, and the wind becomes "sheltered" on the downstream (leeward) side of the wave crest. The pressure difference between the windward (left) and leeward (right) sides of the crest transfers energy from the wind to the wave, causing it to grow. **(c)** The wind's speed is highest well above the water and decreases until it reaches zero at the ocean surface. At a critical height where the wind's speed equals the phase speed of the wave, the wind's shear resonates with the wave and transfers further energy to it. (Image by Donna Padian.)

The problem then lay dormant for 15 years. It was not until World War II that it was taken up again, when accurate meteorological predictions of waves and surf became crucial for the transport and amphibious landings of supplies and soldiers. Researchers working in the US—mainly Harald Sverdrup and Walter Munk at the Scripps Institution of Oceanography in California—needed predictions of the heights of locally generated waves in "fetch"-limited seas, the type of storm waves that crashed onto beaches near Normandy, France, during D-Day. They used simple scaling arguments to estimate those wave heights from the intensity and duration over which the wind was blowing. The relation between those variables forms the foundation of an empirical model for how winds locally generate waves, and these relationships are still used nowadays.

In the UK, meanwhile, Group W—whose initial stood for "waves"—primarily focused on swells that affected the South Pacific during wartime. The group became interested in how those long-wavelength waves traveled great distances. They turned to 19th-century mathematicians Augustin Louis Cauchy and Siméon Poisson, whose work had predicted swell behavior. They answered the question of how waves emanate from a rock dropped into a pond. Researchers used that theory—modeling distant storms as "the rock dropped into the pond"—to predict arrival times of those swells.

Around the time Group W was working on swell predictions, physics Nobel laureate Peter Kapitza re-examined Jeffreys's sheltering mechanism.[7] But instead of focusing on airflow separation in the thin layer of air close to the water's surface, he considered airflow separation events on the scale of a wavelength. And although that work received little attention, his intuition regarding large airflow-separation events near wave crests was well founded.

Munk supplemented those theoretical works with some much-needed observations. But he did not restrict his attention to fetch relationships. Working with Charles Cox on a seminal study of photographs taken from a B-17 bomber,[8] he investigated the connection between wind speed and the slope of the sea surface. Their observations led to the realization that the two variables are strongly correlated. Building on that work, Munk further suggested that short-wavelength waves are the ones most actively coupled to the wind and that the intensity of that coupling, or growth, depends on their slope.[9] Even so, the mechanism behind that fundamental process, which Munk called "an inconvenient sea truth," is still not understood.

Miles and Phillips

In his 1956 review of the subject, Group W member Fritz Ursell wrote that oceanographers' understanding of wave generation by wind was "unsatisfactory."[10] Two young scientists answered his call to action: the University of California's John Miles and Cambridge University's Owen Phillips.

The so-called Miles mechanism[11] is a shear-flow instability in the spirit of the original theory of Kelvin and Helmholtz. Miles, however, had the crucial insight to account for a mean wind profile, based on flow properties close to a boundary. He produced a semilaminar inviscid model, in which the shear-flow instability occurs at a critical height—specifically, where the wind speed matches the phase speed of the growing wave (see figure 2). The instability couples the surface wave to its induced perturbation at that height, and the coupling, in turn, removes energy and momentum from the wind and produces waves with it. The growth rate of those waves depends not on the wind speed or its gradient, but on the curvature of the wind profile at the critical height.

Just as Miles was publishing his paper, Phillips proposed a mechanism that relies on a resonance between surface waves and pressure fluctuations in the wind.[12] That is, wind has a turbulent component—composed of an ensemble of eddies—as it blows over water. The pressure disturbances associated with those eddies do work on the water surface, generating wavelets. If those wavelets, and hence the pressure perturbations, travel at the speed of a free-surface gravity wave, a resonance occurs, and the wavelet can grow into a wave. (See the article by Callum Shakespeare, PHYSICS TODAY, June 2019, page 34, and the article by Erdal Yiğit and Alexander S. Medvedev, page 40.)

The validity of Phillips's theory has only recently been explored through detailed laboratory experiments and numerical simulations of turbulent flow. The results suggest that the theory is accurate at early stages in the wave-generation process and provides a mechanism by which the ocean surface goes from being perfectly smooth to rippled (see figure 2). Once those ripples attain an amplitude of a few millimeters, other growth mechanisms occur and the nonlinear transfer of energy between waves becomes dominant.

Despite their appeal, both mechanisms have limitations. On the one hand, the Phillips theory predicts that wave amplitudes grow linearly in time but weakly. And as mentioned above, that seems to apply only during the early stages of growth. Once waves become larger and longer, the Miles mechanism becomes dominant: Waves grow exponentially in time and with a much larger growth rate than happens in the Phillips mechanism.

Miles's mechanism, however, ignores turbulence and its effects on wave-induced perturbations of atmospheric flow. For short waves, the critical height lies close to the surface—a region where turbulent eddies are advected slowly compared with their lifetime. It is then reasonable to think that those eddies can interact with the waves and that alternative, possibly turbulent, processes can hence become dominant in that short-wavelength regime. Other limitations of the Miles mechanism include that it does not treat nonlinear effects in the flow,[13] the effects of viscosity, and interactions between short- and long-wavelength waves.

Difficulties of corroborating theories

The Phillips and Miles theories assume that ocean waves are not steep, treat waves as (nearly) monochromatic, and do not account for the multiscale nature of turbulent flow. In an attempt to overcome those shortcomings, Stephen Belcher and Julian Hunt proposed, in 1993, an extension of Jeffreys's sheltering mechanism to turbulent flow.[14] They used tools from turbulence theory to quantify how the pressure difference caused by sheltering is affected in the presence of turbulent eddies. The resulting mechanism is based solely on the deformation of airflow on the leeward face of the wave. And it produces realistic estimates of wave growth for short waves.

In realistic field conditions, the sea surface can be described by a broadband wave spectrum that interacts with turbulent air. Hence theoretical growth rates should be tested against observations in the laboratory and in the field. A full validation, however, would require knowledge of the airflow structure. Moreover, the Miles critical height is proportional to the length of the waves. Hence, for short waves, which are expected to be strongly coupled to the wind, that height is just tenths of a centimeter from a quickly changing surface. That makes atmospheric properties just above the wave extremely difficult to measure.

To experimentally confirm the theories of wave growth, researchers must verify the consequences of Miles's theory. Those consequences include the form of the streamlines predicted by the theory and the scaling of the wave growth rate with wind speed. Furthermore, because of the scarcity of accurate measurements near the ocean surface, one must generally approximate the expression for the wind profile from boundary-layer theory. Several important scaling parameters arise from that theory—the roughness length scale is one example—and they have proven hard to constrain because they are strongly modulated by the wave field. Despite the difficulties, the predictions and observations of wave growth largely agree for long waves.[13]

The use of Miles's theory, and simple extensions of it, forms the basis for modern wind–wave growth parameterizations—that is, S_{in}—that are used in spectral wave models. Those models do not usually resolve short waves, so their spectral shape and response to wind forcing are parameterized using only

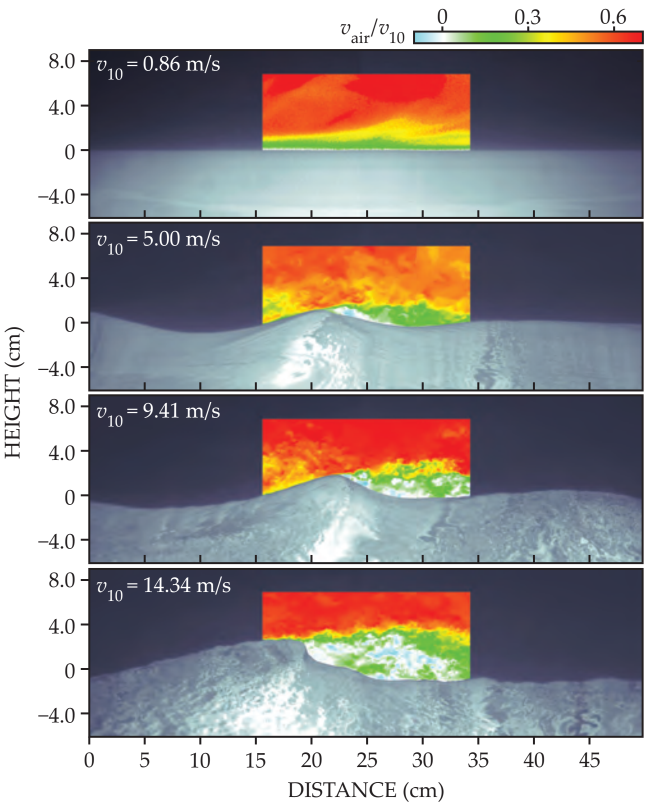

FIGURE 3. AIRFLOW SPEED, in color, as measured above water waves. In this laboratory experiment, each panel illustrates the horizontal flow of the air above the water surface as a function of different wind and wave conditions. The colors represent the airflow speed v_{air} divided by the wind speed v_{10} that would be measured at 10 m above the water's surface. The airflow goes from being approximately laminar at low wind speeds to turbulent at high speeds, with the airflow being strongly "separated" from the water surface near the crest of steep waves. (Courtesy of Marc Buckley and Fabrice Veron.)

(possibly incomplete) physical grounds as a basis.[15,16]

Current research challenges

Recent advances to understanding how wind generates waves have been driven by technological developments in computational and observational capabilities, and in improved theoretical formulations of the problem.

Measurements made in the laboratory and in the field have shown the existence of a critical height—a necessary feature of Miles's theory—and its importance in controlling the flux of momentum to long waves. Natural reference frames, which measure distances normal and tangential to the surface, not from some fixed point, have greatly clarified the observational data. The development of large-eddy simulations of the atmospheric boundary layer have also shed light on various regimes, particularly for low winds and long waves. In those regimes, significant momentum can even be transferred from the waves back to the atmosphere.

The dynamics of short waves are more complex than those of long waves because of the effects of wave breaking. The steep slopes that occur when waves break induce 3D airflow separation downwind of the wave crest (see figure 3). Wave-breaking events become even more important as the wind strength increases to hurricane levels. Experiments in laboratory facilities capable of producing such extreme conditions indicate that the reattachment of separated air streamlines occurs much less frequently at higher wind speeds than at lower ones and isolates the waves from the bulk airflow. That modification of properties in the near-surface flow has proven to be important in hurricane-strength conditions and is an active area of research.

Some experiments and computations that resolve the fully coupled air–water turbulent system have already been achieved and are starting to become more routine. Experimentally, the challenge is to perform measurements of the turbulence in air and water simultaneously. Computationally, the challenge is to solve the two-phase Navier–Stokes equations over the wide range of scales that are involved.

Figure 3 shows snapshots of the airflow in recently performed laboratory experiments just above water waves of various slopes and in increasing wind intensities. Figure 4 shows an example of fully coupled simulations of waves growing under a turbulent boundary layer. Both experiments and simulations resolve the airflow close to the surface. The numerical simulations have the added benefit of capturing the full 3D velocity and pressure fields along with the water flow.

Both studies highlight the complex coupling between water waves and the turbulent wind. The numerical simulations in figure 4, produced by members in one of our groups (Deike's), set the stage for an investigation of all 3D fields, such as the pressure field at the ocean's surface. That's a notoriously difficult field to measure in the lab because waves move so rapidly.

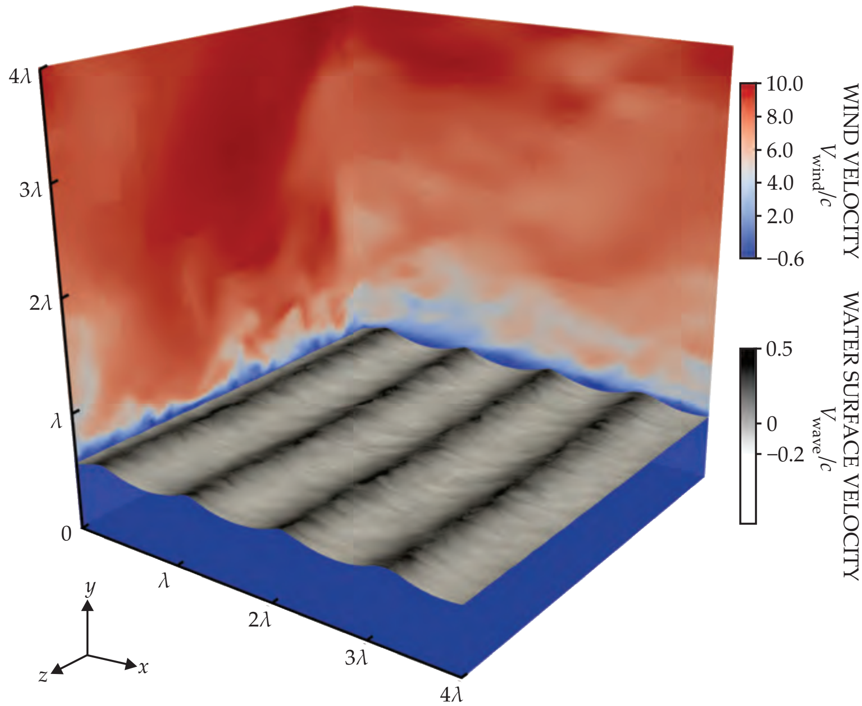

FIGURE 4. NUMERICAL SIMULATIONS of waves growing under a turbulent wind akin to the strongest wind conditions in figure 3. The waves' slope $2\pi A/\lambda = 0.2$, where A is the waves' amplitude and λ is their wavelength. Notice the three-dimensional structures in the dimensionless wind-velocity field V_{wind}/c near the surface of the water; c represents the waves' phase speed. The dimensionless wave-velocity field V_{wave}/c varies not only in the wind-forcing direction (x) but also in the transverse (z) direction along the crests. The simulation solves the 3D Navier–Stokes equations for the water flow, airflow, and interface between them. (Courtesy of Jiarong Wu, Stéphane Popinet, and Luc Deike.)

An analysis of energy and momentum transfer from the wind to the waves is another example. It could help further test the proposed theories on wave growth in various regimes.

Although many details remain elusive, a combination of theoretical, numerical, laboratory, and field advances have led researchers to a better understanding of wave generation by wind. The simple question of how it happens will, no doubt, continue to inspire research into the underlying structure of the ocean and coupled ocean–atmosphere models in a warming climate.

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THE DEMONS HAUNTING

Katie Robertson

The contradictory implications of statistical mechanics have worried physicists and philosophers for centuries. Does our present-day knowledge allow us to exorcize those philosophical demons?

Thermodynamics is a strange theory. Although it is fundamental to our understanding of the world, it differs dramatically from other physical theories. For that reason, it has been termed the "village witch" of physics.[1] Some of the many oddities of thermodynamics are the bizarre philosophical implications of classical statistical mechanics. Well before relativity theory and quantum mechanics brought the paradoxes of modern physics into the public eye, Ludwig Boltzmann, James Clerk Maxwell, and other pioneers of statistical mechanics wrestled with several thought experiments, or demons, that threatened to undermine thermodynamics.

Despite valiant efforts, Maxwell and Boltzmann were unable to completely vanquish the demons besetting the village witch of physics—largely because they were limited to the classical perspective. Today, experimental and theoretical developments in quantum foundations have granted present-day researchers and philosophers greater insights into thermodynamics and statistical mechanics. They allow us to perform a "quantum exorcism" on the demons haunting thermodynamics and banish them once and for all.

Loschmidt's demon and time reversibility

Boltzmann, a founder of statistical mechanics and thermodynamics, was fascinated by one of the latter field's seeming paradoxes: How does the irreversible behavior demonstrated by a system reaching thermodynamic equilibrium, such as a cup of coffee cooling down or a gas spreading out, arise from the underlying time-reversible classical mechanics?[2] That equilibrating behavior only happens in one direction of time: If you watch a video of a wine glass smashing, you know immediately whether the video was in rewind or not. In contrast, the underlying classical or quantum mechanics are time reversible: If you were to see a video of lots of billiard balls colliding, you wouldn't necessarily know whether the video was in rewind or not. Throughout his career, Boltzmann pursued a range of strategies to explain irreversible equilibrating behavior from the underlying reversible dynamics.

Boltzmann's friend Josef Loschmidt famously objected to those attempts. He argued that the underlying classical mechanics allow for the possibility that the momenta are reversed, which would

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THERMODYNAMICS

The Flammarion engraving, which depicts a man putting his head through the edge of the cosmic firmament, has often been used to symbolize humanity's quest for scientific knowledge. (Engraving from Camille Flammarion, *L'atmosphère: météorologie populaire*, 1888, p. 163/public domain.)

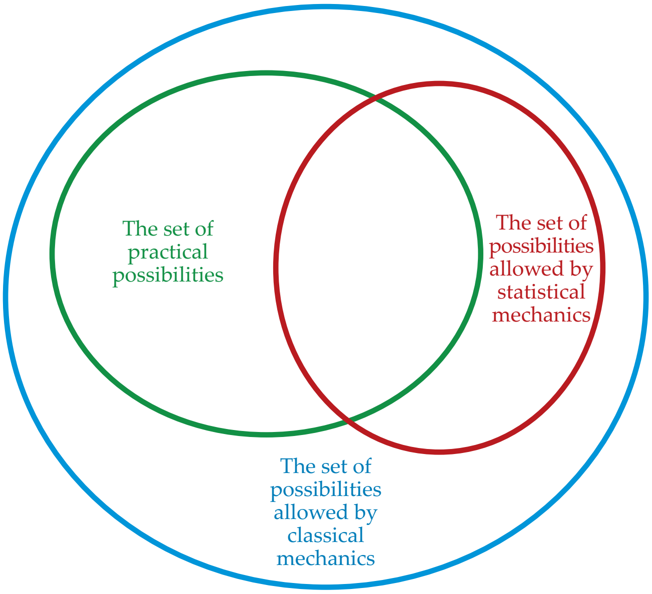

FIGURE 1. THE VARYING SETS of possibilities allowed by various physical theories can be depicted by intersecting ovals. The set of possibilities allowed by classical mechanics (the blue oval) contains both the set of possibilities allowed by statistical mechanics (the red oval) and the set of possibilities that can be practically realized in real life (the green oval). Loschmidt's demon is possible under the classical regime because that paradigm allows for the possibility of a system's momenta being reversed. Statistical mechanics, on the other hand, says that systems can't decrease their entropy on average, which rules out any demonic activities. Although Ludwig Boltzmann believed that a demon that reverses the momenta is practically impossible, the spin-echo experiment has proven that it can be done in rare cases. Loschmidt's demon is thus inside the blue and green ovals but not the red oval.

lead to the gas retracing its steps and "anti-equilibrating" to the earlier, lower-entropy state. Boltzmann challenged Loschmidt to try to reverse the momenta, but Loschmidt was unable to do so. Nevertheless, we can envision a demon that could. After all, it is just a matter of practical impossibility—not physical impossibility—that we can't reach into a box of gas and reverse each molecule's trajectory.

Technological developments since Loschmidt's death in 1895 have expanded the horizons of what is practically possible (see figure 1). Although it seemed impossible during his lifetime, Loschmidt's vision of reversing the momenta was realized by Erwin Hahn in 1950 in the spin-echo experiment, in which atomic spins that have dephased and become disordered are taken back to their earlier state by an RF pulse. If it is practically possible to reverse the momenta, what does that imply about equilibration? Is Loschmidt's demon triumphant?

Unlike the other two demons we will encounter, we can make our peace with Loschmidt's. It turns out that the spin-echo experiment is a special case; most systems approach equilibrium instead of retracing their steps back to nonequilibrium states. But Loschmidt's demon vividly reminds us that the underlying laws of mechanics allow for a system to retrace its steps. Why don't we see that possibility? Why doesn't a gas compress back into a smaller volume? Why don't eggs unsmash or cups of coffee spontaneously warm up?

The answer lies in the distinction between laws and initial conditions. Consider a stone thrown into a pond. The initial condition—the stone hitting the pond—explains why we see ripples going outward. In contrast, we never see ripples converge inward and propel a stone from the pond's depths because the required initial condition would be fiendishly difficult to set up. Similarly, the initial conditions typical in systems involving gases explain why they approach equilibrium. But special initial conditions with finely tuned correlations could lead to instances of anti-equilibration, such as your coffee spontaneously getting hotter or stones being propelled out of ponds. In other words, anti-equilibration is possible according to the microdynamic laws of physics, but only if systems have highly atypical initial conditions.

Maxwell's nimble-fingered demon

By far the most famous hypothetical demon in physics is the one conjured up by Maxwell in 1867 (see figure 2). He envisioned a being that observes individual molecules in a gas-filled box with a partition in the middle. If the demon sees a fast-moving gas molecule, it opens a trapdoor in the partition that allows fast-moving molecules through while leaving slow-moving ones behind. Repeatedly doing that would allow the

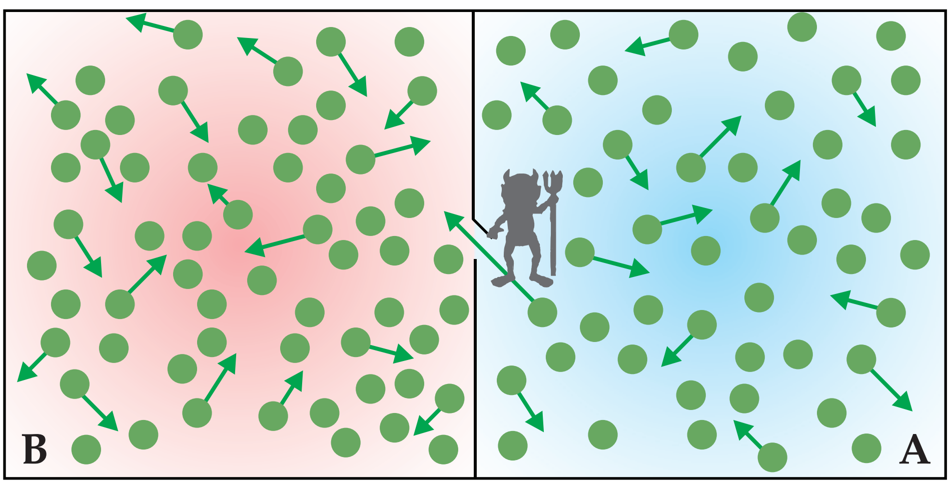

FIGURE 2. MAXWELL'S DEMON is a hypothetical being that can observe individual molecules in a gas-filled box with a partition in the middle separating chambers A and B. If the demon sees a fast-moving gas molecule, it opens a trapdoor in the partition to let fast-moving molecules into chamber B while leaving slow-moving ones behind. Repeating that action would allow the buildup of a temperature difference between the two sides of the partition. A heat engine could use that temperature difference to perform work, which would contradict the second law of thermodynamics.

buildup of a temperature difference between the two sides of the partition. A heat engine could use that temperature difference to perform work, which would contradict the second law of thermodynamics.

Is Maxwell's demon in the same category as Loschmidt's demon—namely, a mere matter of practical difficulty rather than physical impossibility? Maxwell thought so. According to philosopher of physics Wayne Myrvold, Maxwell believed that "only our current, but perhaps temporary, inability to manipulate molecules individually . . . prevents us from doing what the demon would be able to do."[3]

When Maxwell was writing over 150 years ago, the possibility of manipulating individual molecules might have seemed far-fetched, but that's no longer the case today. From purpose-built experimental apparatuses to molecular machines found in nature, devices similar to Maxwell's demon abound. For example, biomolecular machines use ratchet-style mechanisms[4] akin to the version of Maxwell's demon devised by Richard Feynman in a 1962 lecture.

Moreover, researchers have seemingly been able to realize Maxwell's demon in experiments. One group in Tokyo led by Masaki Sano devised a demon-style experiment in 2010 (see the article by Eric Lutz and Sergio Ciliberto, PHYSICS TODAY, September 2015, page 30). Using a tilted optical lattice to manipulate a particle, Sano's team created a "spiral staircase" that, on average, the particle tended to descend. By using a CCD camera, the experimenters monitored the fluctuations in the particle's position in real time. When the particle fluctuated upward, they altered the voltage and trapped it in a higher position, much like the demon shutting the trapdoor (see figure 3). By repeating that process, Sano was able to gradually move the particle upward and do work.

Are such ingenious devices genuine Maxwellian demons? Do they invalidate the second law? Although their mechanisms seem to be demonic, some careful entropic accounting is in order. A process contravenes the second law only if the entropy of the total system decreases. In a familiar example, the entropy of an ideal gas decreases during isothermal compression, but the compensating increase in the heat bath means that the system's total entropy increases. Is there a compensating entropic increase in the environment that thwarts any attempt to violate the second law?

That question has been vigorously debated since Maxwell's demon was first posited.[5] Although some philosophers of physics disagree,[6] many physicists now believe that there is an entropy cost associated with the demon's activities. Because those ingenious devices lead to entropy increases elsewhere in the greater system, none of them truly violate the second law. The entropic costs stem from the demon's operation. To run, it must perform a feedback operation: If the molecule is fast moving, the demon opens the door, but if the molecule is slow, the demon closes the door.

That requires the demon to have a memory, which must be reset at the end of the cyclic process. But resetting the memory has an entropic cost, which can be quantified by a principle proposed by Rolf Landauer in 1961. It states that entropy increases by $k_B \ln 2$ per bit of information that is reset, where k_B is Boltzmann's constant. In other words, erasing information will cost you. Landauer's principle thus forges a connection between thermodynamics and information theory—although the precise nature of their relationship remains controversial.

Nonetheless, to my eyes, Landauer's principle explains why no matter how ingenious or nimble fingered today's experimenters may be, they can't build engines that reliably violate the second law of thermodynamics and solve the global energy crisis. Once we peek behind the scenes and account for the environment, we see that today's alleged Maxwellian demons are deft illusionists rather than true magicians.

Much of the activity in contemporary thermal physics arises from the melding of quantum information theory with thermodynamics. Can going quantum release the demon from the shackles imposed by Landauer's principle? Sadly, it cannot. The principle holds for all forms of dynamics that preserve phase-space volume, and both classical and quantum mechanics fulfill that criterion. Moreover, there may even be extra entropic costs associated with quantum operations: The Landauer limit cannot be reached by quantum computation.[7]

Quantum steampunk

Maxwell's philosophical speculations about the nature of thermodynamics and statistical mechanics extended beyond his demon. To reconcile those probabilistic theories with his classically trained worldview, Maxwell made two philosophical claims: First, thermodynamics applies only to systems with many degrees of freedom, and second,

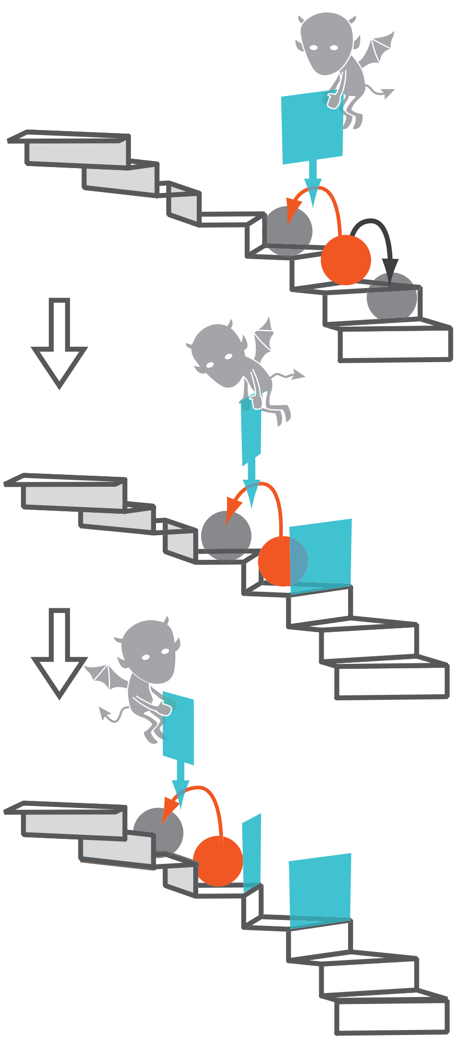

FIGURE 3. A DEMON-STYLE EXPERIMENT was devised by Masaki Sano's group in 2010. It used a tilted optical lattice to create a "spiral staircase" that the particle tended to descend over time. The experimenters monitored the fluctuations in the particle's position in real time, and when the particle fluctuated upward, they altered the voltage and trapped it in a higher position. As illustrated here, the experiment can be analogized to Maxwell's demon shutting the trapdoor. (Adapted from S. Toyabe et al., *Nat. Phys.* **6**, 988, 2010.)

it is anthropocentric and contingent on our human viewpoint. Do those philosophical postulates hold up today?

Experimental and theoretical developments in thermodynamics since the mid 20th century have demonstrated that Maxwell's first claim was incorrect. In Maxwell's time, thermodynamics was characterized by the steam engines that powered the Industrial Revolution, but today the thermodynamic revolution—the subfield that Nicole Yunger Halpern has termed "quantum steampunk"—is on the atomic scale.[8] Quantum heat engines, for example, were first proposed in 1959 by Derrick Scovil and Erich Schulz-DuBois, who demonstrated how a three-level maser could function as a heat engine. With the advent of quantum information theory, those tiny thermodynamic systems now provide fodder for an entire subfield.[9] Other types of quantum thermal machines use microscopic systems such as multilevel atoms, qubits, and quantum dots as the working substance in a heat engine.

How do quantum and classical heat engines differ? Additional resources are available in the quantum regime: Entanglement and coherence can be used as "fuel." Still, no one has found a way to cheat the second law.[10] Perhaps that is to be expected. After all, Seth Lloyd held that "nothing in life is certain except death, taxes, and the second law of thermodynamics."

FIGURE 4. LAPLACE'S DEMON is a fictional entity endowed with the knowledge of the position and momentum of every molecule in the universe. (*Laplace's Demon*, by Ele Willoughby, linocut, 2011.)

Nonetheless, the two types of engines differ in fascinating ways. In traditional thermodynamics, maximum Carnot efficiency is achieved only when processes are carried out quasi-statically, or infinitely slowly, which means that the power generated tends toward zero. That constraint led to the development of finite-time thermodynamics, and within that framework there are other limits to efficiency. Quantum machines can be more efficient than their classical counterparts in that finite-time regime—but both remain bounded by the Carnot limit.[11]

If thermodynamics is not limited to macroscopically large systems, is it universal? Many physicists believe that it is. Albert Einstein once said that "it is the only physical theory of universal content concerning which I am convinced that, within the framework of applicability of its basic concepts, it will never be overthrown."[12] Nowadays thermodynamics is used to understand topics as varied as quantum thermal engines, globular clusters of stars, black holes, bacterial colonies, and—more controversially—the brain.[13]

Is thermodynamics anthropocentric?

What about Maxwell's second philosophical claim, that thermodynamics is a feature of our perspective on reality? As he wrote in an 1877 *Encyclopædia Britannica* article, the distinction between ordered and disordered motion that is fundamental to thermodynamics "is not a property of material things in themselves, but only in relation to the mind which perceives them."[14] Maxwell's viewpoint has proven influential over the years. Percy Bridgman, for example, echoed Maxwell when he asserted in 1941 that "thermodynamics smells more of its human origin than other branches of physics—the manipulator is usually present in the argument."[15]

Why is that? Consider the honeybee as an example. The insect sees a garden very differently than we do because its eyes are sensitive to a different part of the electromagnetic spectrum than ours are. The claim that thermodynamics is anthropocentric, or observer dependent, implies that thermodynamic features such as entropy might look different—or not exist at all—if we were a different type of creature. In that view, thermodynamics would be analogous to a pair of rose-tinted glasses through which we understand and perceive the world but do not see how it actually looks.

In that way, Maxwell's ideas tie thermodynamics to beings like us. Because quantum mechanics has made many people comfortable with the observer being seemingly ineliminable from physics, that might not seem unusual. But Maxwell wasn't appealing to some generic observer like the honeybee.

He believed that thermodynamics is specifically anthropocentric. As he wrote in the same *Encyclopædia Britannica* article, "It is only to a being in the intermediate stage, who can lay hold of some forms of energy while others elude his grasp, that energy appears to be passing inevitably from the available to the dissipated state."[16] Understanding that anthropocentrism is fraught with challenges. For example, it seems undeniable that cups of coffee cool down regardless of what we know about them or our perspective on reality.

How worrying we find the possibility of anthropocentrism is determined by nothing less than our stance on the scientific enterprise itself. Are scientists actually learning about the deep nature of reality in a manner independent of our perspective? Or is science just a mere tool or instrument that we should use to "shut up and calculate"? The debate over scientific realism, as it is termed, has raged unresolved for centuries. But recent developments in quantum thermodynamics offer some hope for those who would like to rid thermodynamics of its human smell.

Leaving ignorance out of it

In classical statistical mechanics, the key postulate—often called the fundamental assumption—is that each accessible microstate of a system must be equally likely. But how should we understand probabilities in statistical mechanics? That question has received considerable attention over the years from trailblazers such as Boltzmann, Paul Ehrenfest, and Tatiana Ehrenfest-Afanasyeva. Here we will narrow our attention to one dominant view, popularized by physicist Edwin Jaynes, which argues that the fundamental assumption of statistical mechanics stems from our ignorance of the microscopic details. Because the Jaynesian view emphasizes our own ignorance, it implicitly reinforces the idea that thermal physics is anthropocentric. We must assume each state is equally likely because we don't know which exact microstate the system is in.

Here we are confronted by our third and final philosophical specter: the demon first articulated by Pierre Simon Laplace in 1814 (see figure 4). Laplace's demon is a hypothetical observer that knows the position and momentum of every molecule in the universe. In other words, it knows the exact microstate of every system in the universe.

In statistical mechanics, the entropy of a system is commonly expressed by the Gibbs formula, $S_G = \int \rho \ln \rho \, d^N\mathbf{q} \, d^N\mathbf{p}$, where $\rho(\mathbf{q}, \mathbf{p})$ represents a probability distribution, such as the microcanonical distribution, over the phase space of positions and momenta, $\{\mathbf{q}_1, \ldots, \mathbf{q}_N; \mathbf{p}_1, \ldots, \mathbf{p}_N\}$, that the system of N particles could occupy. But for Laplace's demon, $\rho = 1$, because it knows the system's exact microstate with certainty. That omniscience means the demon would calculate the system's Gibbs entropy to be zero! The Jaynesian view of statistical mechanical probabilities thus has a radical consequence: It means that the value assigned to the Gibbs entropy depends on our knowledge of the world.

Does Laplace's demon threaten the Jaynesian view of statistical mechanics? Not quite. Fortunately, it, too, can be exorcised by shifting to a quantum perspective on statistical mechanics. In classical statistical mechanics, probabilities are an additional ingredient added to the system's microdynamics. According to the Jaynesian view, they are a necessary step because of our ignorance. But in the quantum case, probabilities are already an inherent part of the theory, so there is no need to add ignorance to the picture. In other words, the probabilities from statistical mechanics and quantum mechanics turn out to be one and the same.

But in quantum mechanics, the Born rule implies that a quantum state encodes probabilities of different measurement outcomes. How can those probabilities give rise to the familiar probability distributions from statistical mechanics? That question is especially tricky because quantum mechanics assigns an isolated system a definite state known as a pure state. In contrast, statistical mechanics assigns such a system an inherently uncertain state known as a maximally mixed state, in which each possibility is equally likely. On the face of it, statistical mechanics and quantum mechanics appear to clash.

The distinctively quantum nature of entanglement holds the key to resolving that seeming conflict[17] (see figure 5). Consider a qubit that is entangled with a surrounding heat bath.

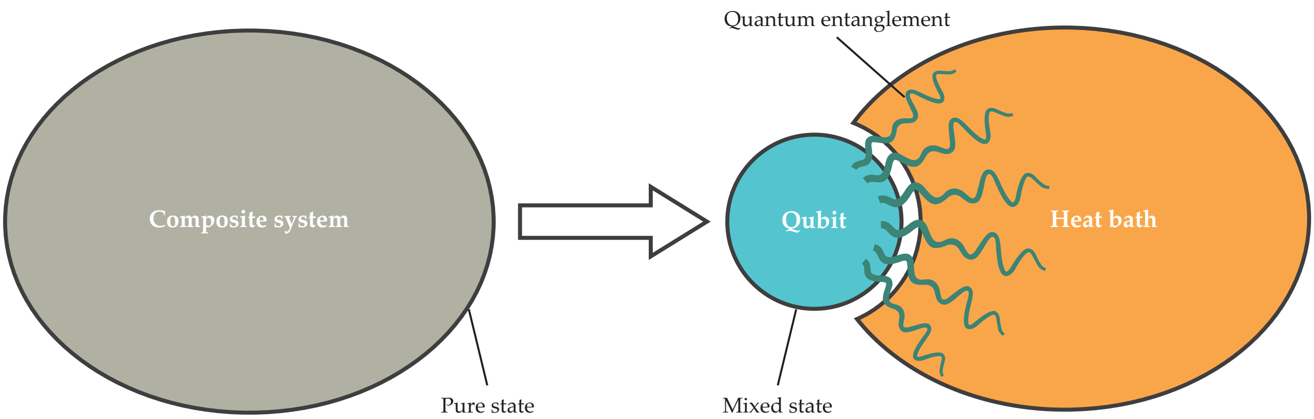

FIGURE 5. QUANTUM ENTANGLEMENT explains why Laplace's demon is vanquished. Consider a qubit and a heat bath that are entangled (at right). If the qubit is taken on its own, it will be in a mixed state, as will the heat bath. But the composite system of the qubit and the heat bath (at left) is in a pure state because when taken as a whole, it is isolated. Assuming the environment is sufficiently large, for almost any pure state that the composite system is in, the qubit will be in a state very close to the state it would be assigned by traditional statistical mechanics. Thus the system acts as if the fundamental assumption of statistical mechanics were true. The probability distribution assigned by statistical mechanics is indistinguishable from the quantum state, which implies that statistical mechanics does not require Jaynes's introduction of "ignorance." Laplace's demon is therefore defanged. (Adapted from S. Deffner, *Nat. Phys.* **11**, 383, 2015.)

Because they are entangled, if one of the two systems is taken on its own, it will be in an intrinsically uncertain state known as a mixed state. Nonetheless, the composite system of the qubit taken together with the heat bath is in a pure state because when taken as a whole, it is isolated. Assuming that the surrounding environment—namely, the heat bath—is sufficiently large, then for almost any pure state that the composite system is in, the qubit will be in a state very, very close to the state it would be assigned by traditional statistical mechanics.

In other words, the system under study—the qubit—behaves as if the composite system were in a maximally mixed state, namely, as if each microstate of the composite system is equally likely. The nature of the probabilities is ultimately quantum, but the system acts as if the fundamental assumption of statistical mechanics were true. The quantum description thus leads to a probability distribution indistinguishable from that of statistical mechanics.

How does that conclusion vanquish Laplace's demon? Quantum mechanics assigns probabilities to events not because we don't know their exact value but because both we and the demon cannot know that value. Probabilities are an intrinsic and inescapable part of quantum mechanics. When it describes the entangled system taken on its own, Laplace's demon cannot know any more than us.

Arthur Eddington proclaimed in 1928 that the second law of thermodynamics held "the supreme position among the laws of Nature." Any theory that argued against it, he wrote, would "collapse in deepest humiliation."[18] Nearly 100 years later, Eddington has yet to be proven wrong.

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40 Years of Scientific Innovation and Instrument Development

Daniel Polancic
Global Sales Director,
Quantum Design

As the research community experiences a new "quantum revolution," Quantum Design (QD) approaches its 40th year in business. Quantum principles were at the heart of QD's first major product, the Magnetic Property Measurement System (MPMS). This magnetometer achieves high sensitivity by utilizing a SQUID detection circuit, which leverages the quantized behavior of magnetic flux in a superconducting loop containing a Josephson tunneling junction.

The MPMS proved to be just the right instrument during the boom in high-temperature superconducting research in the 1980s and afterward. The drive to discover higher transition temperatures in new materials shaped the development of the MPMS, which features high throughput and quality results. Additional automated measurement capabilities for the MPMS followed, providing researchers sophisticated turnkey techniques like AC susceptibility. Soon customers requested the ability to conduct other measurements in the variable temperature and magnetic field environment afforded by the MPMS.

In response, QD introduced the Physical Property Measurement System (PPMS) to provide a flexible platform with many new options for characterizing samples. As automatic and easy to use as the MPMS, the PPMS gives users wider access to thermal and electrical measurements, new types of magnetic characterization, greater magnetic fields, and lower temperatures. Those turnkey options help novice researchers quickly acquire high-quality data, and the open platform enables advanced users to integrate their own custom experiments.

As liquid helium became increasingly expensive and scarce, QD developed cryogen-free versions of those platforms to offer researchers more sustainable instrumentation. In parallel, recapture and reliquefaction systems were introduced to support existing instruments. Throughout QD's history, our company has maintained a strong relationship with customers, enabling us to better understand their goals and develop instruments that reflect the needs of the research community.

In the midst of the burgeoning quantum revolution, Quantum Design's technology remains on the cutting edge. Core products like QD's MPMS3 and PPMS DynaCool continue to be indispensable tools in the characterization of new and engineered materials with novel quantum mechanical properties. The new 7 T optical cryostat, OptiCool, is enabling unprecedented optical access to materials under high magnetic fields, while the AFM insert (AFSEM) makes correlative microscopy more accessible for characterizing 2D and nanoscale systems and devices.

In 2014 Quantum Design became a more active participant in the promotion of STEM education for college undergraduates. Through our Quantum Education Initiative, whose goal is to advance the education of the next generation of quantum scientists and engineers, QD has created curriculum and equipped teaching laboratories with modern instrumentation.

By working with our customers to identify key needs and areas for improvement, Quantum Design has been at the forefront of materials research for the past 40 years. We at QD feel that the future holds exciting potential. In partnership with scientists from around the world, who explore new frontiers of discovery and try to answer fundamental questions, QD strives to develop the next generation of technologies that will help make a better and brighter future for everyone.

US DEPARTMENT OF ENERGY

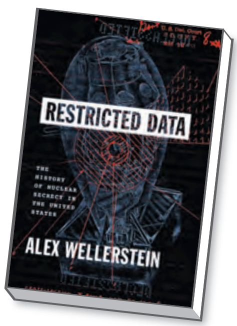
THE MUSHROOM CLOUD from the Castle Bravo thermonuclear test on 1 March 1954 at Bikini, an atoll in the Marshall Islands. Fallout from the explosion rained down on the Japanese fishing vessel *Lucky Dragon No. 5* and caused radiation sickness among its 23 crew members.

The conundrums of atomic secrecy

In 1979 the magazine *The Progressive* published an article featuring a series of illustrations purportedly showing the interior workings of a hydrogen bomb. Its author was Howard Morland, a journalist and activist with little physics training. Morland produced the illustrations by interviewing weapons scientists and reading encyclopedia articles, including one written by Edward Teller, the physicist who in 1951 first worked out the key design concept behind the H-bomb in collaboration with mathematician Stanislaw Ulam. Morland's drawings depicted the Teller–Ulam invention accurately enough that the US government took him, his editors, and the magazine's publisher to federal court to bar the article's publication.

The government eventually dropped the case, but by then multiple conundrums at the heart of US nuclear secrecy had come to light. Morland had no security clearance and no access to restricted

Restricted Data
The History of Nuclear Secrecy in the United States
Alex Wellerstein
U. Chicago Press, 2021. $35.00



data—the special classification given to nuclear secrets by the Atomic Energy Act of 1946. If he could uncover the secret of the H-bomb, had it really been a secret? Had the government inadvertently leaked the secret itself by trying to suppress Morland's drawings? Was nuclear secrecy compatible with American principles of free speech and democracy? Could the government control scientific knowledge? Should it want to?

As historian Alex Wellerstein explains in *Restricted Data: The History of Nuclear Secrecy in the United States*, nuclear secrecy is a tale of such irresolvable tensions. Wellerstein divides the story into three epochs. The first unfolded during World War II, when a scheme by scientists to self-censor their research on nuclear fission rapidly gave way to the Manhattan Project's formal secrecy. Information related to the bomb project was controlled by a strict policy of compartmentalization, enforced by the project's military overseer, Leslie Groves.

The second epoch began with the onset of the Cold War, when the government used the new legal category of restricted data to divide "dangerous" knowledge related to nuclear weapons from "safe" knowledge related to peaceful atomic research and the civilian nuclear power industry. In practice, the boundary between safe and dangerous knowledge proved unstable; the peaceful atom could all too easily be turned toward militaristic ends.

That bipolar secrecy system faced increasing challenges during the book's third epoch: the 1960s and beyond. During that period, commercial actors hoping to profit from research on isotope-separating centrifuges and laser-driven thermonuclear fusion bumped against some of the most closely guarded nuclear secrets. Meanwhile, secret seekers like Morland believed that prying restricted data from the state's hands would strike a blow against the nuclear complex on behalf of democracy and peace.

It may seem inevitable that the US nuclear secrecy regime gradually expanded into the sprawling behemoth we know today, but Wellerstein highlights several moments when history might have turned out differently. Alternative futures were especially thinkable in the immediate postwar years. The scientist–administrators who implemented secrecy as a wartime exigency saw the severest restrictions as temporary, and they considered a range of schemes for taming the atom. J. Robert Oppenheimer, for example, argued for pursuing a control strategy that was focused more on nuclear materials than on knowledge encoded in documents. In the end, the crucial category of restricted data might never have existed had Groves not chosen in early 1946 to leak information about a Soviet espionage ring in Canada just as a congressional committee was working out new legislation for postwar atomic policy.

Readers of PHYSICS TODAY may be familiar with Wellerstein's engaging articles in this magazine and elsewhere (see PHYSICS TODAY, May 2012, page 47; April 2017, page 40; and December 2019, page 42); his blog, also titled *Restricted Data*; and his project NUKEMAP, which allows users to simulate the effects of nuclear detonations. Based on interviews and years of tireless spadework in government archives, the present book showcases his talents as a researcher and a skillful writer of narrative and analysis.

One of *Restricted Data*'s many strengths is its reconstruction of the work of those inside the state who debated, designed, and performed the day-to-day bureaucratic practices of secrecy. The effect is one of demystification: Nuclear secrecy has been powerful, but it has also been messy, inconsistent, and often self-defeating. As Wellerstein wryly puts it, "the censors are people too."

Yet the final chapters caution us from taking comfort in that observation. At the end of the Cold War, activists successfully lobbied for declassifications confirming the nuclear complex's vast harms to the environment and human health. The government disclosed that about 20% of US nuclear tests were never officially announced and that in the 1940s human radiation experiments were conducted without patients' informed consent. But secrecy reform has had limited ability to disrupt the nuclear system. The US government's post–Cold War openness was quickly reversed as new threats emerged and officials reasserted secrecy in the name of nuclear nonproliferation. "If anything," Wellerstein concludes, "it is the fact that so little has changed, despite the now many decades separating the end of the Cold War from the present, that is most striking."

Even if the censors wanted to alter the immense structures of the nuclear state, they would not be much better equipped to do so than the outsiders. In the realm of nuclear weapons, knowledge is not always power. One lesson of *Restricted Data* is that although a serious restructuring of the nuclear enterprise may begin with the exposure of its secrets, it cannot end there.

Benjamin Wilson
Harvard University
Cambridge, Massachusetts

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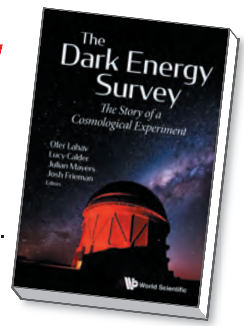
THE DARK ENERGY SURVEY'S imaging camera was mounted on the Víctor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory in Chile, which is pictured here under the night sky with part of the Milky Way visible.

Unifying two fields

The Dark Energy Survey
The Story of a Cosmological Experiment
Ofer Lahav et al., eds.
World Scientific, 2020. $128.00



Although astronomy has been a part of physics for centuries, it maintained a separate culture until the relatively recent realization that some central problems in fundamental physics were best attacked using astronomical techniques. I can remember a time when I served on a Department of Energy panel and was advised never to use the word "telescope," because higher-level committees would frown on the unwanted incursion into astronomy. Equally telling is the warning I received as an undergraduate in the 1970s: Only "failed physicists" go into astronomy. That is no longer true. The two cultures are now conjoined by cosmology, and there is little distinction between astronomers and astrophysicists.

The Dark Energy Survey: The Story of a Cosmological Experiment documents a collaboration that epitomizes the recent melding of those two cultures. As the title suggests, it outlines how physicists and astronomers successfully attacked one of the most perplexing questions in physics: What explains the accelerated expansion of the universe? The book chronicles the collaboration's history from its genesis as a mere idea in 2003 through the six-year observational program it ran from 2013 to 2019. As one might expect, the book presents an informative overview of the project's many scientific discoveries. But it is equally valuable for its depiction of the nuts and bolts of fashioning an experiment spanning different scientific cultures and funding agencies.

The centerpiece of the Dark Energy Survey (DES) was an imaging camera built for the project and mounted at the prime focus of the Víctor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory in Chile. In each pointing, the camera observed 3 square degrees in five colors. The resulting observations were mosaicked together to form a final composite image that spanned 5000 square degrees. Researchers used four different methods, set out in 2006 by the US Dark Energy Task Force, to achieve the overarching goal of measuring the cosmological equation-of-state parameter w with an accuracy of a few percent.

The book provides an excellent description of the science behind those four methods and delves deep into the details of data taking, computer modeling, scientific management, and the search for hidden uncertainties in the results. Its depiction of the ways in which DES scientists guarded against confirmation bias is especially interesting. They kept the intermediate results of the four primary methods hidden by blinding the analysis of the data. Only at the very end was the final result of the experiment—which found that w is closely consistent with the cosmological constant first postulated by Albert Einstein—revealed to the investigators. The blinding gave the scientific community confidence that the result reflects the data and not the scientists' expectations.

The histories of important experiments are often written well after the fact and can be unconsciously shaped by the memories of a few individuals who worked on those experiments—namely, those who write down their recollections. The account of the DES in the present book will be important for historians of science because it was written during the final stages of the project and not years later, when its full impact will have been realized. Each chapter was written by different groups of authors and emphasizes different aspects of the project's evolution.

The Dark Energy Survey is unique because it is neither a pure narrative of a project nor a review article about scientific discoveries. Aside from historians, the audience for such a book is not apparent. At times it feels as if the intended audience is the DES collaboration itself—it includes details that could only be interesting to those that were part of the history. But that is not a criticism, because the book comes off as an honest and intimate telling of the history. The flow of the prose is choppy, because a different group wrote each chapter, and readers will likely skip to the sections that interest them most.

The final chapters include observations of the collaboration by anthropologists, a philosopher, and artists in residence. The book ends with a poem by Amy Catanzano, which in part reads,

> Here at Cerro Tololo,
> a furnace of galaxies
> spirals the heart,
> weaving sparks
> and thick
> mists –
>
> Each galaxy is a performance
>
> hypnotizing space

We don't think of the scientific practice as being anything like a theatrical performance, but in some ways it is. In my generation, astronomers observed and physicists did experiments. The past cultures of astronomy and physics evolved their own distinct personalities. The book describes an important milestone in the history of the unification of the two fields and provides an excellent summary of the methods used to explore one of the greatest mysteries in physics today: dark energy. Not every reader will find every chapter interesting, but all readers with science backgrounds will find in some chapters a mirror of their experience.

Nicholas B. Suntzeff
Texas A&M University
College Station

Foundation

David S. Goyer and Josh Friedman
Apple TV+, 2021

Isaac Asimov's Foundation trilogy is one of the seminal sci-fi series of the 1940s and 1950s, but it contains little action and suspense. To modernize the story for television, Apple TV+'s well-acted new series foregrounds action only hinted at in the book series and enhances it with superb technology and costume design. Researchers may be intrigued by the incredible sky elevator. They may also appreciate how *Foundation* addresses the continuing debate on scientific reason versus religious faith and engagingly depicts a character calculating their position in space without the help of a navigation computer. After a shaky start, the series gently pulls you into its world and asks: How much free will do individuals actually have? –PKG

Frequently Asked Questions About the Universe

Jorge Cham and Daniel Whiteson
Riverhead Books, 2021. $28.00

Why can't I travel back in time? What happens if I get sucked into a black hole? Where did the universe come from? Those are just a few of the questions addressed by engineer-turned-cartoonist Jorge Cham and physicist Daniel Whiteson in their new book, *Frequently Asked Questions About the Universe*. Inspired by listeners of their podcast, *Daniel and Jorge Explain the Universe*, Cham and Whiteson use nontechnical language and humor to discuss the most up-to-date theories about the cosmos and humans' place in it. Illustrated with Cham's science-themed cartoons, the book is both educational and entertaining. –CC

Among the Stars

Ben Turner
Disney+, 2021

Within the first 10 minutes of the documentary series *Among the Stars*, viewers see firsthand how any spacewalk can quickly go wrong. While he was working on the exterior of the International Space Station in July 2013, astronaut Luca Parmitano began to feel water pooling in his helmet. At risk of drowning in his suit, he had to rush back to the station in utter darkness. Footage from the helmet cameras and mission control bring home the agonizing few minutes before Parmitano made it back. But that harrowing tale is just a prelude to the documentary's main story: the mission to repair the Alpha Magnetic Spectrometer. We follow Parmitano and fellow astronaut Andrew Morgan as they train to fix the instrument, which they ultimately did over four spacewalks between November 2019 and January 2020. The six-part series brings home the meticulous preparation behind every minute in space. –RD PT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LUDDY SCHOOL OF INFORMATICS, COMPUTING, AND ENGINEERING
INDIANA UNIVERSITY

Faculty Position in Quantum Photonics and Nanoscale Optics Engineering

The Luddy School of Informatics, Computing, and Engineering at Indiana University-Bloomington (IUB) invites applications for a tenure track assistant professor position in experimental Quantum Photonics and Nanoscale Optics Engineering in the Department of Intelligent Systems Engineering (ISE) to begin in August 2022. ISE is a diverse department exploring the applications of modern computing and technology across a broad range of areas, from sensors to robotics to high performance computing to bioengineering. This position is part of IUB's Emerging Areas of Research initiative which is funding significant growth in these areas through the Quantum Science and Engineering Center (IU-QSEc: https://qsec.sitehost.iu.edu/).

Candidates should show commitment to the collaborative and transdisciplinary development of the IU-QSEc and ISE's activities in quantum information science and engineering, including, but not limited to quantum computation, simulation, sensing, and communication.

ISE faculty are expected to develop an active, externally-funded research program.

The successful candidate will have the opportunity to collaborate with existing efforts in multi-functional structured optical fibers for Quantum Interconnects (QuIC) (https://fames.indiana.edu/), conventional and quantum networks, and quantum simulation with both trapped atoms and ions (https://ultracold.physics.indiana.edu, https://iontrap.physics.indiana.edu/).

We seek candidates committed to excellence in teaching courses of interest to a broad range of both undergraduate and graduate engineering students and whose teaching fosters diversity and inclusion.

Duties will include research, teaching multi-level courses both online and in person, participating in course design and assessment, and service to the School.

Applicants should have a demonstrable potential for excellence in research and teaching and a Ph.D. in engineering, physics, or a related scientific discipline expected before August 2022.

Applications received before December 1, 2021 will be assured full consideration; however, the search will remain open until a suitable candidate is found. Candidates should review application requirements, learn about IU, Luddy School, and benefits, and apply online at:

https://indiana.peopleadmin.com/postings/11553

Questions may be sent to Prof. James A. Glazier (jaglazier@gmail.com) or Prof. Alexander Gumennik (gumennik@iu.edu).

Indiana University is an equal employment and affirmative action employer and a provider of ADA Services. All qualified applicants will receive consideration for employment without regard to age, ethnicity, color, race, religion, sex, sexual orientation, gender identity or expression, genetic information, marital status, national origin, disability status or protected veteran status.

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and nanoscience

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

Andreas Mandelis

Characterization of nanomaterials and nanostructures

A collaboration between Bruker and the Technical University of Denmark Nanolab has produced the new Optimus 2 detector head. As part of Bruker's new augmented on-axis transmission Kikuchi diffraction (TKD) solution in electron backscatter diffraction (EBSD), the detector head enhances the company's eFlash EBSD detectors for crystal-orientation mapping on electron-transparent samples. Bruker says that the augmented on-axis TKD solution and new hardware and software expand the EBSD applications range and accelerate and improve the characterization of nanomaterials and nanostructures in a scanning electron microscope. Among other advancements, Optimus 2 improves spatial resolution to 1.5 nm and lower by optimizing beam focus and astigmatism settings before the TKD map acquisition. ***Bruker Nano GmbH***, *Am Studio 2D, 12489 Berlin, Germany, www.bruker.com*

Multiple laser combiner

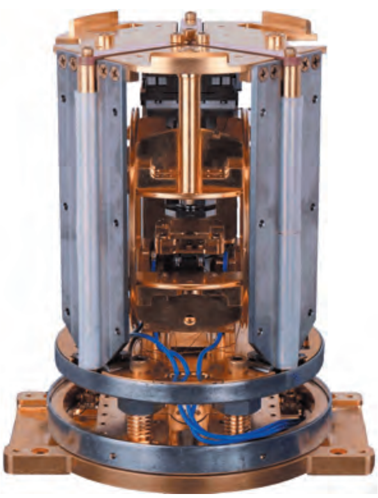
Hübner Photonics has expanded its C-FLEX laser combiner family by introducing the compact C8. The platform is available in three sizes that can be equipped with four, six, or eight high-performance Cobolt lasers. The flexible laser combiners are available in a range of standard application-specific configurations or can be customized to user needs. They are easy to install and field-upgradeable. A very broad range of wavelengths can be integrated: 375 nm to 1064 nm, with an output power of up to 1000 mW. The C-FLEX series includes both diode lasers with high-speed modulation capability and diode-pumped lasers with single-frequency operation. Multiple fiber outputs and the option to integrate high-power lasers from the Cobolt 05-iE series make the C-FLEX C8 suitable for applications in bioimaging, Raman spectroscopy, and holography. ***Hübner Photonics Inc***, *2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Laser wavelength meter for IR applications

To facilitate the characterization of IR lasers, Bristol Instruments has added the NIR2 system to its 671 laser wavelength meter series. The 671 NIR2 is suitable for use by scientists and engineers who need to know the exact wavelength of CW lasers that operate from 1.0 μm to 2.6 μm. It uses a Michelson interferometer–based design to measure laser wavelength to an accuracy of ±0.0002 nm. A convenient prealigned fiber-optic input ensures optimum alignment of the laser under test and allows the system to be placed in an out-of-the-way location, which saves optical bench space. ***Bristol Instruments Inc***, *770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

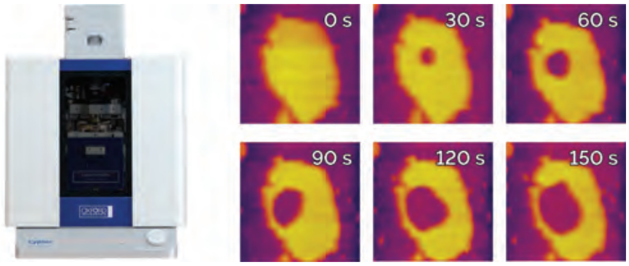
Fast electron-multiplying CCD camera

According to Raptor Photonics, its digital monochrome Kestrel 1000 is one of the fastest and most sensitive scientific frame-transfer electron-multiplying (EM) CCD cameras available. The Kestrel 1000 features ultralow readout noise while running at 1000 fps in full frame and up to 1800 fps when focusing on a region of interest. With EM gain on, it offers less than 1 e^- read noise. Its 128 pixel × 128 pixel back-thinned sensor with 24 µm × 24 µm pixel size provides high image resolution in low-light applications. The camera delivers up to 95% quantum efficiency for optimum photon collection, strong response from the UV to the near-IR, and ultrawide bandwidth from 350 nm to 1100 nm. The Kestrel 1000 uses a 16-bit A/D converter and a standard CameraLink output and is cooled to −20 °C. Applications include high-resolution fluorescence and hyperspectral imaging, particle image velocimetry, and adaptive optics and astronomy. ***Raptor Photonics Ltd****, Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, UK, www.raptorphotonics.com*



Automated scanning SQUID microscope

High Precision Devices, a FormFactor company, has introduced its IQ1000 scanning SQUID microscope. It is used to study the dynamics of trapped magnetic flux, or magnetic vortices, that can negatively impact superconducting circuit operation. IQ1000 users can image magnetic vortices in devices cooled through the superconducting transition temperature in controlled magnetic fields. It also enables studies of vortex dynamics in the circuit using *XYZ*-vectored magnetic fields, direct manipulation of vortices using the sensor field coils, and precise control of sample temperature. With rapid scan speed and process automation, the IQ1000 is the first commercial product of its kind to enable unattended and high-throughput characterization, according to the company. Those characterization techniques and capabilities may advance the development of operationally robust superconducting circuits. ***High Precision Devices Inc****, 4601 Nautilus Ct S, Ste 100, Boulder, CO 80301, https://hpd-online.com*



Video-rate atomic force microscope

The Cypher VRS1250 video-rate atomic force microscope (AFM) from Oxford Instruments Asylum Research enables scan rates up to 1250 lines/s and frame rates up to 45 fps. According to the company, the high speed will enable researchers to capture nanoscale details of dynamic events that were previously inaccessible. Those include biochemical reactions, 2D molecular self-assembly, etch and dissolution processes, and more. According to the company, the Cypher VRS1250—alone among high-speed AFMs—can also support a full range of modes and accessories, which makes it suitable for large interdisciplinary research groups and shared imaging facilities with multiple projects. To generate fast, high-resolution imaging, the microscope's small-spot cantilever detection maintains a very low signal-to-noise ratio even on the extremely small cantilevers required for video-rate AFM. ***Oxford Instruments America Inc****, 300 Baker Ave, Ste 150, Concord, MA 01742, www.oxinst.com*

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Richard Fitzgerald, Publisher

Scientific CMOS camera for microscopy

Teledyne Photometrics has launched its Kinetix22 scientific CMOS camera for demanding applications such as spinning-disk confocal imaging and light-sheet microscopy. The Kinetix22 delivers a unique combination of speed, sensitivity, low noise, high resolution, and versatility, according to the company. It features a 22 mm field of view and a 2400 pixel × 2400 pixel sensor with 6.5 μm × 6.5 μm pixel size. Back illumination allows weak signals to be displayed as high-quality images; the camera achieves 95% quantum efficiency. Four modes let users prioritize different camera specs and optimize imaging: The 8-bit speed mode offers 498 fps across the full frame, the 12-bit sensitivity mode offers low 1.2 e^- read noise at approximately 90 fps, the 16-bit dynamic-range mode has large full-well capacity for varied signal levels in the sample, and the 16-bit subelectron mode offers electron-multiplying CCD-like sensitivity with 0.7 e^- read noise. ***Teledyne Photometrics***, *3440 E Britannia Dr, Ste 100, Tucson, AZ 85706, www.photometrics.com*

Improvements to multichannel event timers

PicoQuant has announced a free firmware update for its MultiHarp 150 4P, 8P, and 16P high-throughput multichannel event timers. One major improvement is the change in temporal resolution from 10 ps to 5 ps, which does not affect other parameters, such as the excellent data throughput or ultrashort dead time. The update also provides a programmable input hysteresis for noise suppression in difficult environments. According to the company, those MultiHarp 150 models provide the best temporal resolution on the market for event timers that have subnanosecond dead time. Comprising electronics for time-correlated single-photon counting, they are suitable for fast, precise fluorescence-lifetime imaging using PicoQuant's rapidFLIM and high-throughput multichannel photon correlation. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com* PT


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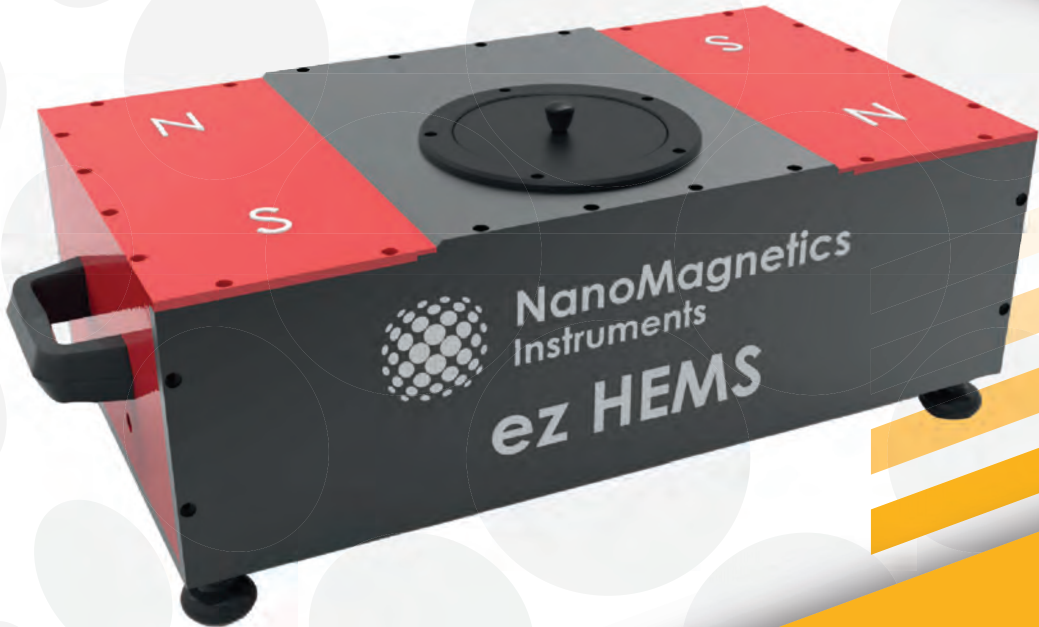

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Isamu Akasaki

Isamu Akasaki, a 2014 Nobel laureate in physics who brought highly efficient general lighting for the 21st century to people all over the world, passed away on 1 April 2021 in Nagoya, Japan, at age 92.

Akasaki was born on 30 January 1929 in Chiran, Kagoshima, in the southern part of Japan. When he was a child, his father gave him ore specimens that started his strong interest in crystals. He graduated from the Faculty of Science at Kyoto University with a BS degree in 1952. He then joined Kobe Kogyo Corp, where he developed fluorescent materials for the surfaces of cathode-ray tubes. That was his first encounter with luminescence without heat.

In 1959 Akasaki joined Nagoya University as an assistant professor working under Tetsuya Arizumi. There he was intoxicated by the allure of germanium crystal growth. In 1964 he received his doctorate of engineering from Nagoya with a thesis titled "Vapor phase epitaxial growth of Ge."

Akasaki moved to the Matsushita Research Institute Tokyo in 1964. There he became one of the principal investigators of R&D projects and encountered LEDs. His group was instrumental in the commercialization of gallium phosphide–based green and red LEDs. That achievement, however, left him unsatisfied because he thought he was merely following the pioneering work done in the US and Europe. He therefore started nitride research in 1967, initially focusing on aluminum nitride as a cathodoluminescence material. He started growing gallium nitride crystals by molecular-beam epitaxy (MBE), at that time a new crystal-growth technology.

Several group members strongly objected to Akasaki's choice of MBE. Despite that opposition, the Ministry of International Trade and Industry provided funding for Akasaki to set up a test project in 1974. He was able to merely observe blue cathodoluminescence from MBE-grown GaN and could not fabricate LEDs. After the project, he shifted his focus to vapor-phase growth using halogens—so-called halide vapor-phase epitaxy—and succeeded in creating a metal-insulator-semiconductor prototype blue LED.

But Akasaki still thought the development of the blue LED followed the LED invented by Jacques Pankove, Herbert Maruska, and their group members at RCA and Stanford University. After his success, Akasaki wanted to continue research to establish an original blue LED. Unfortunately, the people at the top of Matsushita did not listen to him and decided to stop research on blue LEDs. So Akasaki made up his mind to move in 1981 to Nagoya University, where he developed a new crystal-growth method, metal-organic vapor-phase epitaxy. At that time, few other organizations in the world were continuing to explore GaN. Most researchers considered it to be extremely difficult to grow GaN single crystals and impossible to grow p-type GaN, so many of them abandoned such studies. According to Akasaki, his situation was like "going alone into the wilderness," although I think that as a pathfinder who sought frontier research fields, he probably enjoyed it.

Akasaki gave several lectures to the public before and after receiving the Nobel Prize. After presentations, young researchers sometimes asked him, "I cannot decide my research subject. Could you help me?" He always answered by saying, "If you are wondering what to do, do what you want to do." That answer really epitomized him perfectly. He always wanted to be a trailblazer of fields where no one had been before. I believe that aspect of his personality came from his experience; he always followed his interest and passion.

Akasaki empowered young people not only by giving them advice but also by setting up awards especially for the younger generation. In 2010 he donated the money he received the previous year as a Kyoto Prize recipient and established the Nagoya University Akasaki Award, for which awardees must be 35 or younger. He also established awards presented by the Japan Society of Applied Physics and the Japanese Association for Crystal Growth.

According to the Nobel Foundation, Akasaki's contributions "hold great promise for increasing the quality of life for over 1.5 billion people around the world who lack access to electricity grids." Now GaN is seen not only as an LED material but also as a key component for

Isamu Akasaki

laser diodes and high-frequency devices that will help in achieving carbon neutrality and realizing 5G and post-5G wireless communications systems. The "wilderness" in which Akasaki made his home has now been cultivated into a prosperous and fruitful field that many researchers around the globe are harvesting to bring happiness to people worldwide. As one of his young researchers, I thank the true pioneer Isamu Akasaki for leaving us his wonderful legacy.

Hiroshi Amano
Nagoya University
Nagoya, Japan

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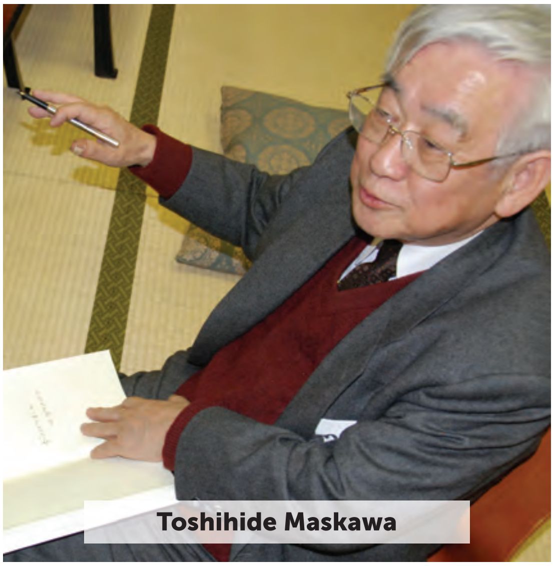
Toshihide Maskawa

Toshihide Maskawa died on 23 July 2021 from gingival cancer at age 81 in Kyoto, Japan. He shared the 2008 Nobel Prize in Physics with Makoto Kobayashi "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature" and with Yoichiro Nambu, who discovered "the mechanism of spontaneous broken symmetry in subatomic physics."

Born in Nagoya, Japan, on 7 February 1940, Maskawa entered Nagoya University in 1958 and stayed there for graduate school. Although he was fascinated by mathematics, he decided to join the particle-theory group of Shoichi Sakata, who proposed the Sakata model, an early precursor to the quark model. Maskawa received his PhD in particle physics from Nagoya in 1967 and spent three years at the university as a postdoc. That period gave him a chance to meet Kobayashi, a brilliant student, who entered Nagoya's graduate school in 1967. They wrote several papers together at the university.

In 1970 Maskawa moved to Kyoto University as an assistant professor. He was later joined by Kobayashi, who became an assistant professor in April 1972. Early that May, Kobayashi and Maskawa, or KM, started their collaboration on possible origins of *CP* violation in renormalizable field theories of weak interactions proposed by Sheldon Glashow, Abdus Salam, and Steven Weinberg. The two completed their work by the summer. They showed it is possible to incorporate *CP* violation if there are six types of quarks. Their paper, published in *Progress of Theoretical Physics* in February 1973, drew little attention until 1976 because only three types of quarks had been discovered at the time of publication.

Times changed after the discovery of the fourth quark in 1974 and the fifth lepton in 1975. Many people started to speculate about the possibility of six quarks. In 1975 Hirotaka Sugawara and Sandip Pakvasa worked on *CP* violation using the KM paper as a basis. They showed that the KM proposal was indeed a viable description of the known *CP* violation with a reasonable choice of the 3×3 unitary matrix known now as the CKM matrix (the C is for Nicola Cabibbo). The KM paper came to world attention after the Pakvasa and Sugawara paper was published in 1976 in *Physical Review D*. In 2001 the BaBar experiment at SLAC and the Belle collaboration at the KEK research institute both showed that the measured *CP* violation is in remarkable agreement with the KM theory.


Toshihide Maskawa

The KM theory was a beautiful Nagoya flower that bloomed in Kyoto. I asked Kobayashi why they came up with six quarks when only three quarks were known. His answer was simple: "There were four quarks in Nagoya." Inspired by the symmetry between the then-known leptons (electron, muon, and neutrino) and fundamental baryons (proton, neutron, and lambda), the Sakata particle-theory group at Nagoya speculated that three fundamental constituents of hadrons are composite particles of three leptons and "B matter" that carry the baryon number. When two kinds of neutrinos were found in 1962, the Sakata group extended the Nagoya model to include four leptons and four constituents of hadrons. In 1971 Kiyoshi Niu and colleagues discovered a new type of event in an emulsion chamber experiment, and Shuzo Ogawa suggested it was evidence of the fourth quark.

Maskawa moved to the University of Tokyo as an associate professor in 1976. Four years later he went back to Kyoto University as a professor at the Yukawa Institute for Theoretical Physics, where he served as director from 1997 until his retirement in 2003. He then led a research group at Kyoto Sangyo University until 2019. From 2010 to 2018, he was also a director of the Kobayashi–Maskawa Institute for the Origin of Particles and the Universe at Nagoya University.

Maskawa always admired Nambu. What made him happiest about receiving the Nobel Prize was that he shared it with Nambu. When Maskawa went to Kyoto in 1970, he gave my fellow graduate students and me a series of lectures on the spontaneous breaking of chiral symmetry. The first material he chose was the groundbreaking work by Nambu and Giovanni Jona-Lasinio. Maskawa was, however, dissatisfied with the nonrenormalizability of their model, and he focused on proving Nambu's idea in renormalizable theories. Maskawa and Hideo Nakajima examined chiral symmetry breaking in a renormalizable abelian gauge theory. Maskawa made significant contributions to various areas of theoretical physics—for example, constrained systems, the Gribov ambiguity, and supersymmetric nonlinear realizations. They were highly mathematical: One of his favorite books was the *Encyclopedic Dictionary of Mathematics* (1993).

Maskawa delivered his Nobel lecture in Japanese. By speaking in his native tongue rather than in English, he could express precisely what he had in mind. Having experienced the devastation of World War II in his childhood, he became a peace advocate and maintained his antiwar stance throughout his life. During his career, Maskawa's honest and straightforward remarks in the media made him popular. He is greatly missed by his colleagues, friends, family, and the people of Japan.

Kiyoshi Higashijima
Osaka, Japan PT

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Chuck Smith is an emeritus professor of mechanical engineering and mechanics at Lehigh University in Bethlehem, Pennsylvania.

Aerodynamic heating in hypersonic flows

Charles R. Smith

A newly discovered mechanism can help keep the world's fastest jets from overheating.

For the last quarter of the 20th century, Concorde airliners and other supersonic aircraft shuttled wealthy passengers between North America and Europe at speeds of up to 600 m/s (about 1350 mph). The planes were retired in 2003. They had grown prohibitively expensive and worried passengers, who couldn't help but notice that the planes' windows were too hot to touch.

Today, however, several airlines have plans to reinstate jets capable of supersonic (Mach 1) and hypersonic (Mach 5) speeds—the Mach number is the ratio of a plane's speed to the local speed of sound. Mach 5 jets routinely exceed 1500–2000 m/s, depending on their altitude. A jet that fast could fly from New York to Paris in just 90 minutes.

Technical challenges have forestalled their development. The temperature of air passing over a jet increases with Mach number and has been measured at 2200 K on the surface of a plane flying at Mach 5 at an altitude of 20 km. Understanding where and when those high temperatures occur on an aircraft is critical to its performance and safety. This Quick Study explores a newly discovered mechanism that can reduce the heating of a jet's surface.

From laminar to turbulent

According to conventional wisdom, aerodynamic heating of a surface peaks with the onset of turbulence. Its emergence substantially increases the shear stresses in air adjacent to the surface, a process that converts kinetic energy to heat. Figure 1 visualizes a jet's hypersonic boundary layer—the thin layer of air whose flow speed decelerates to zero at the aircraft's bounding surface. The transition from laminar flow to turbulence, which is due to the amplification of air's local velocity and pressure instabilities, is unavoidable as air speed rises.

The image, obtained in a low-temperature hypersonic wind tunnel, is produced by laser scattering from carbon dioxide gas mixed with upstream air. In the cold air above the boundary layer, the gas solidifies into fine particles. But inside the boundary layer, where temperatures are much higher because of energy dissipation, the CO_2 remains gaseous. Light scattering from the cold particles appears white, whereas the gaseous flow appears black. The airflow, initially well ordered and laminar from left to right, is thus seen to become turbulent as air compression and expansion produce an amplifying acoustic wave.

The air is hottest when the flow is turbulent. Surprisingly, though, recent studies have shown that a comparable hot peak can also develop in the laminar region prior to the transition. The IR image, shown in figure 2a, of a flared cone in wind-tunnel experiments run at Mach 6 bears that out. A pre-turbulent heating peak, labeled "SH" for secondary heating, develops in an otherwise lower-temperature region prior to the emergence of the turbulent heating peak (TH).

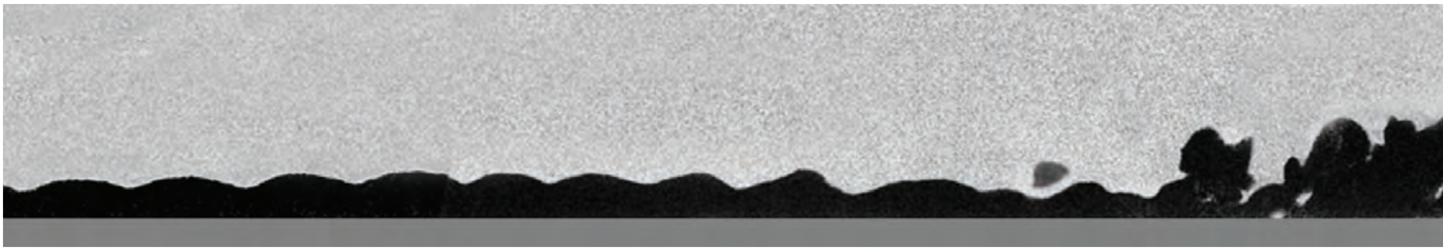
That pre-turbulent peak was first identified three years ago by Cunbiao Lee and his colleagues at China's Peking University. Their research revealed that the SH peak arises from a previously unidentified alternative aerodynamic interaction—one that can either increase or reduce surface heating, depending on circumstances.

Hypersonic heating

What accounts for two separate heating peaks? Three mechanisms convert mechanical energy to thermal energy in a hypersonic flow. The first is the viscous dissipation of kinetic energy by shear stresses adjacent to a surface. The second is also viscous dissipation but the result of normal stresses acting on the compressed air. And the third is the work done by pressure changes acting on the compressed air.

The two viscous energy conversion mechanisms are

FIGURE 1. RAYLEIGH SCATTERING reveals the transition from a laminar to a hypersonic boundary layer. Airflow is left to right in a Mach 6 air tunnel. The amplification of a high-frequency wave in the laminar region at left eventually results in the transition to surface turbulence at right. (Adapted from C. Lee, S. Chen, *Natl. Sci. Rev.* **6**, 155, 2019.)



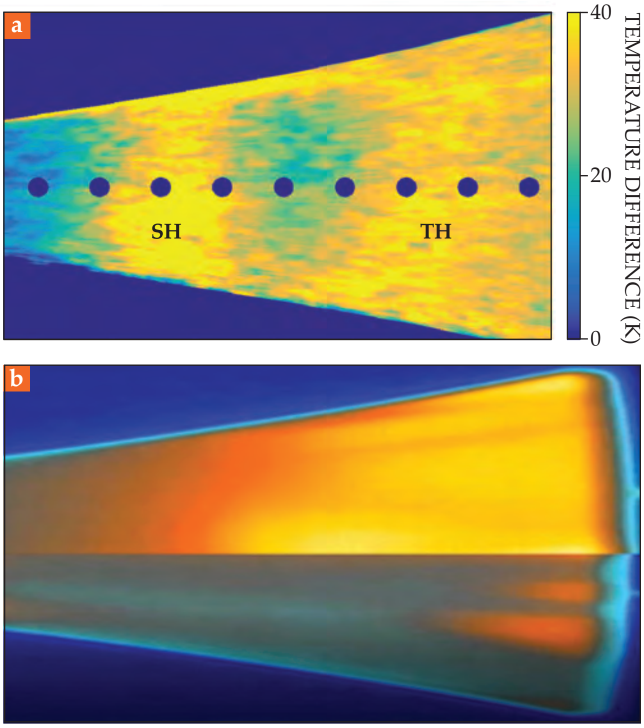


FIGURE 2. THE SURFACE TEMPERATURE of a flared cone rises in a hypersonic wind tunnel whose air is flowing at Mach 6. **(a)** An IR camera captures two (yellow) hot spots: one (SH) that arises from air-compression effects, followed by a second (TH) that arises from turbulent shearing stresses, or turbulence-induced friction. The blue region between SH and TH is the result of cooling by air expansion. Blue dots on the cone signify flush-mounted pressure sensors. (Adapted from Y. Zhu et al., *Phys. Fluids* **30**, 011701, 2018.) **(b)** Surface temperature within the SH region is imaged without (top) and with (bottom) acoustic-wave control introduced at the leading edge of the cone. (Courtesy of Cunbiao Lee.) For a video of the effect, see the online version of this article.

unidirectional—from mechanical to thermal energy—so they always dissipate kinetic energy into heat. Thus, the high-shear stresses that accompany the onset of turbulence always heat a surface. The peak labeled TH in figure 2a is an example.

But the SH peak that occurs prior to the turbulent region is caused by pressure work. Numerical simulations have shown that the magnitude and direction of that work depends on the phase differences between the periodic pressure fluctuations at the surface and air-density fluctuations in the flow. The upshot is that aerodynamic heating by pressure work is bidirectional: It can either augment or diminish the surface heating depending on the sign of those phase differences.

Engineering the cool

Pressure fluctuations behave as acoustic waves, which in hypersonic phenomena are known as second-mode waves. Although fluctuating pressure waves and air-density waves are normally of the same frequency in a second-mode wave, their phase differences—that is, the differences in where the waves peak—can vary. So when the waves are in phase (their peaks coincident), the pressure work will be positive and increase heating. But when the waves are out of phase (their peaks in opposition), the pressure work will be negative and reduce heating. Lee's group first discovered that heating mechanism in 2018, and it was recognized the same year as a new aerodynamic thermal mechanism by Bohua Sun at Xi'an University of Architecture and Technology in China and Elaine Oran at the University of Maryland in College Park.

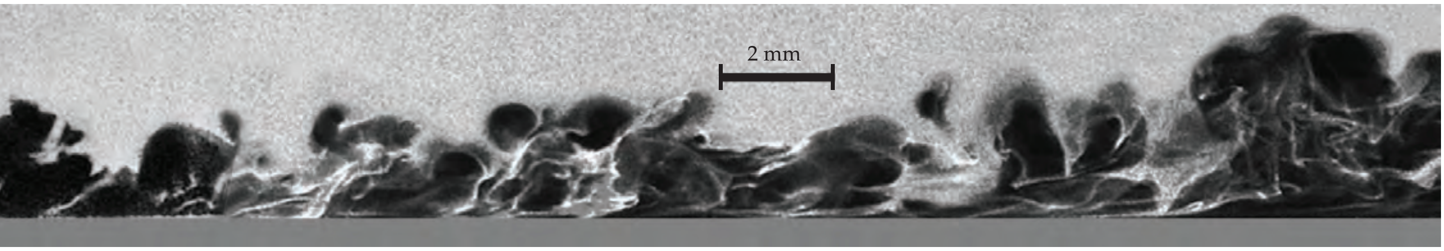
The fluctuating pressure in hypersonic flows behaves as an acoustic wave and is controllable using either a porous surface or a wavy surface. Sound absorption on a porous surface can modify the phase difference of the acoustic wave enough to eliminate the SH peak shown in figure 2a. Alternatively, the use of an appropriately wavy surface can generate an acoustic wave that also modifies the phase of the natural pressure wave enough to reduce how much it heats the surface.

Figure 2b shows two IR images of the region of a flared cone where the SH peak is typically observed. When no wave control is applied to the cone, the upper panel exhibits a large SH peak (yellow). In contrast, the SH peak essentially disappears in the lower panel because of the acoustic control wave introduced by a porous surface near the leading edge of the cone. In general, either a porous or a wavy surface can reduce the surface heating by roughly 25%.

Through a series of detailed studies, Lee's group demonstrated the fundamental behavior of hypersonic transitions between laminar and turbulent flows, discovered a new aerodynamic heating mechanism, and developed successful strategies for controlling it. Through an understanding of the phase relationship between different types of waves, a physical basis for controlling certain aspects of high-Mach-number aerodynamic heating has emerged. How that control is applied to aircraft of the future remains to be seen.

Additional resources

▶ C. Lee, S. Chen, "Recent progress in the study of transition in the hypersonic boundary layer," *Natl. Sci. Rev.* **6**, 155 (2019).
▶ Y. Zhu et al., "Newly identified principle for aerodynamic heating in hypersonic flows," *J. Fluid Mech.* **855**, 152 (2018).
▶ Y. Zhu et al., "Acoustic-wave-induced cooling in onset of hypersonic turbulence," *Phys. Fluids* **32**, 061702 (2020).
▶ B. Sun, E. S. Oran, "New principle for aerodynamic heating," *Natl. Sci. Rev.* **5**, 606 (2018).
▶ W. Zhu et al., "Experimental study of hypersonic boundary layer transition on a permeable wall of a flared cone," *Phys. Fluids* **32**, 011701 (2020). PT



Black carbon frozen in ice

Sea spray, desert dust, and soot from volcanoes and fires are among the aerosols that affect Earth's climate, primarily by scattering or absorbing incoming solar radiation. To provide a long observational record for assessing climate models, Joseph McConnell of the Desert Research Institute in Reno, Nevada, and his colleagues used elemental, chemical-species, and isotope measurements taken from six Antarctic ice cores to reconstruct the variability in black carbon and soot aerosols in the Southern Hemisphere over the past 2000 years. Those aerosols form from the incomplete combustion of fossil fuels, wood, or other biomass. Robert Mulvaney of the British Antarctic Survey, pictured here in 2008, led the drilling of one of the cores, from the northern Antarctic Peninsula. The five other cores were collected by collaborators from the US, Argentina, Germany, and Norway.

In the ice at a depth that corresponds to a time frame of 1297 ± 30 CE, the researchers found a striking threefold increase in the deposition of black carbon in the northern Antarctic Peninsula but not in the continental Antarctic records. A similar depositional pattern in atmospheric models is reproducible if the source of the burning came from a location poleward of 40° S. Tasmania, New Zealand's South Island, and Patagonia satisfy that criterion, and the researchers expected that natural fires in those areas were responsible for the black carbon observations. They were surprised to learn, however, that only the paleofire record from New Zealand matched the timing of the black carbon jump. The Indigenous Maori population first settled there in the early 1300s. (J. R. McConnell et al., *Nature* **598**, 82, 2021; image courtesy of Jack Triest.) —AL

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