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# PHYSICS TODAY

March 2024 • volume 77, number 3

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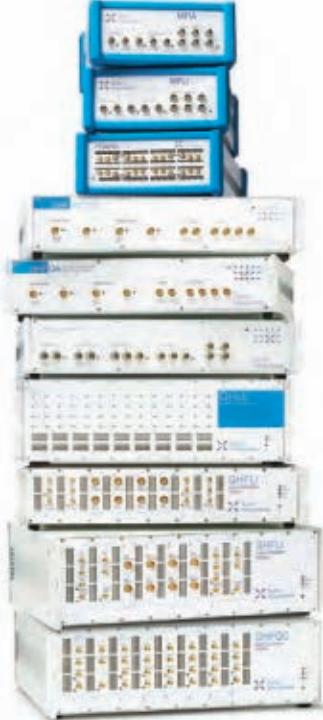
## SOAP-BUBBLE LASERS

**Ammonia as a clean  
energy source**

**Ethics—the department  
chair's perspective**

**Bacterial flagellar  
motors**

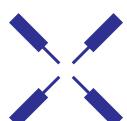
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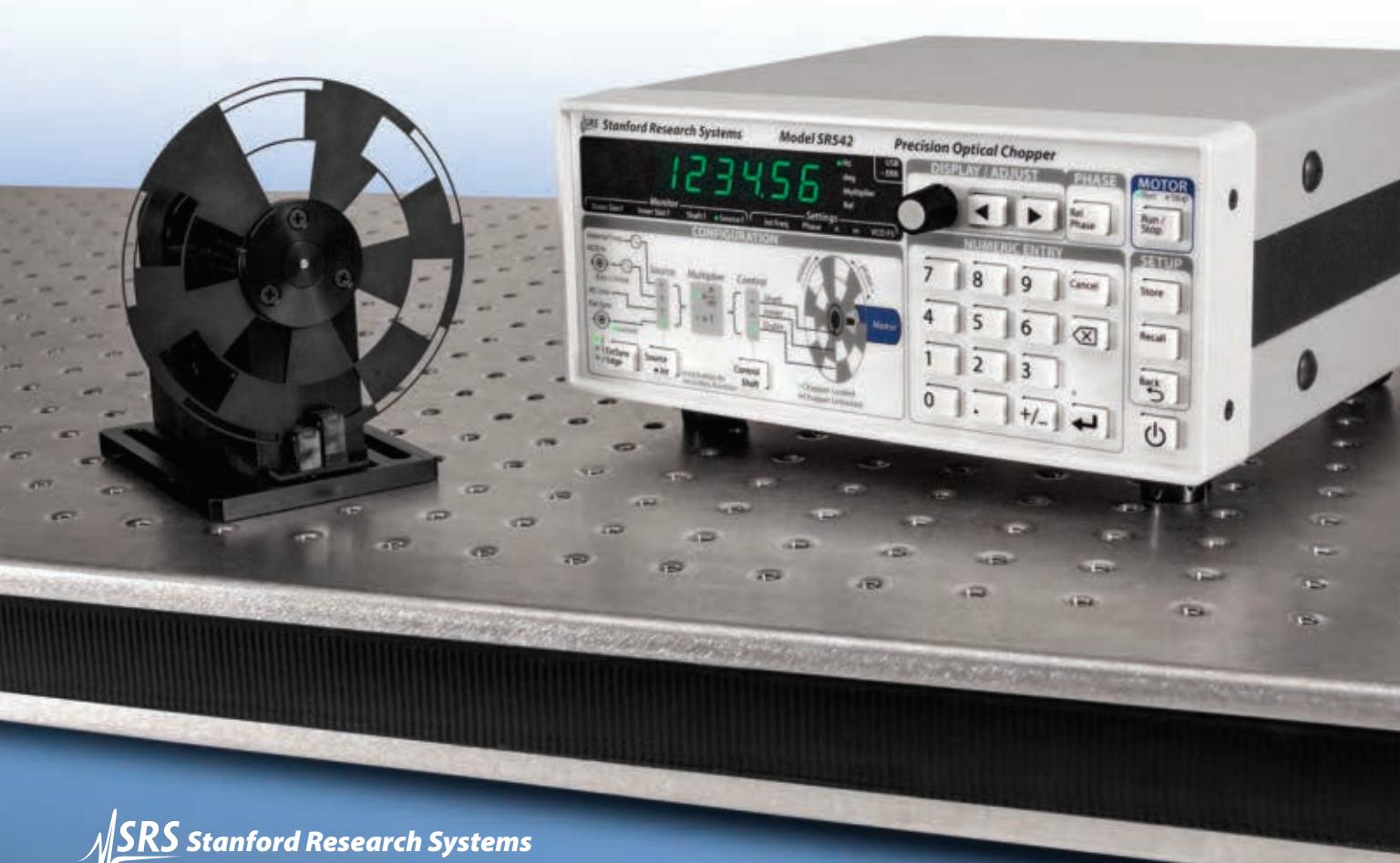
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After World War II, scientists applied the knowledge and experience they gained from nuclear weapons to nuclear astrophysics.



**ON THE COVER:** As a transparent sphere, a simple soap bubble can serve as an optical resonator, which means that with a little fluorescent dye, it can be made into a laser. Bubble lasers are soft and squeezable, and their response to ambient pressure can potentially be harnessed for sensing applications. For more on soap-bubble lasers and their liquid-crystal cousins, turn to the story on **page 12**. (Image by Yuliya Evstratenko/Shutterstock.com.)

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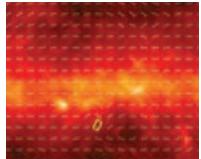
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#### Reactor fuel

Recently the US and the UK launched efforts to encourage the commercial enrichment of high-assay low-enriched uranium. The goal, writes PHYSICS TODAY's David Kramer, is to spur domestic production of a fuel that is needed for most advanced nuclear reactors but is produced primarily in Russia.

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#### Milky Way magnetism

Measuring cosmic magnetic fields presents many observational challenges. Now, using highly accurate distance estimates from the *Gaia* star-surveying satellite, researchers have characterized the fields in five interstellar gas clouds and mapped the magnetic shifts along a spiral arm of the Milky Way.

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#### Cicada overload

This spring in the Midwest and Southeast US, billions of periodical cicadas will surface, make noise, mate, and then die. In a new study, researchers compare cicadas to ferromagnetic spins to explore whether the insects might communicate to synchronize their emergences.

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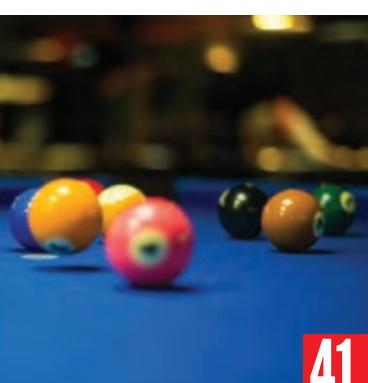
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Richard J. Fitzgerald [rjf@aip.org](mailto:rjf@aip.org)

#### Art and production

Freddie A. Pagani, art director

Nathan Cromer

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#### Editors

Ryan Dahn [rdahn@aip.org](mailto:rdahn@aip.org)

Laura Fattaruso [lfattaruso@aip.org](mailto:lfattaruso@aip.org)

Toni Feder [tf@aip.org](mailto:tf@aip.org)

Abby Hunt [ahunt@aip.org](mailto:ahunt@aip.org)

David Kramer [dk@aip.org](mailto:dk@aip.org)

Alex Lopatka [alopatka@aip.org](mailto:alopatka@aip.org)

Johanna L. Miller [jlm@aip.org](mailto:jlm@aip.org)

Gayle G. Parraway [ggp@aip.org](mailto:ggp@aip.org)

Jennifer Sieben [jsieben@aip.org](mailto:jsieben@aip.org)

R. Mark Wilson [rmw@aip.org](mailto:rmw@aip.org)

#### Online

Andrew Grant, editor [agrant@aip.org](mailto:agrant@aip.org)

Greg Stasiewicz [gls@aip.org](mailto:gls@aip.org)

#### Editorial assistant

Tonya Gary

#### Contributing editors

Cynthia B. Cummings

Bob Holmes

Andreas Mandelis

#### Sales and marketing

Christina Unger Ramos, director [cunger@aip.org](mailto:cunger@aip.org)

Bonnie Feldman

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#### Address

American Institute of Physics

One Physics Ellipse

College Park, MD 20740-3842

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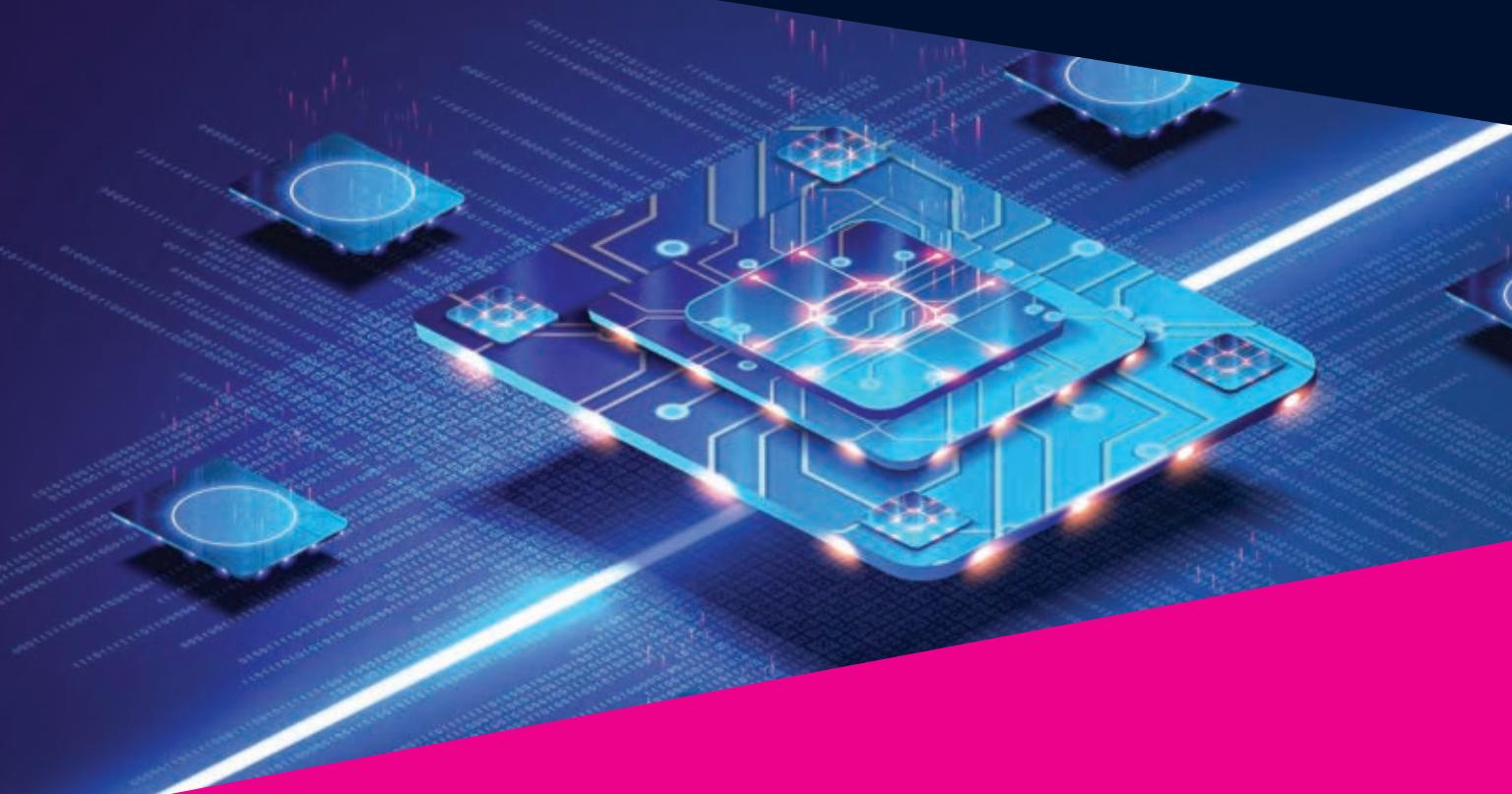
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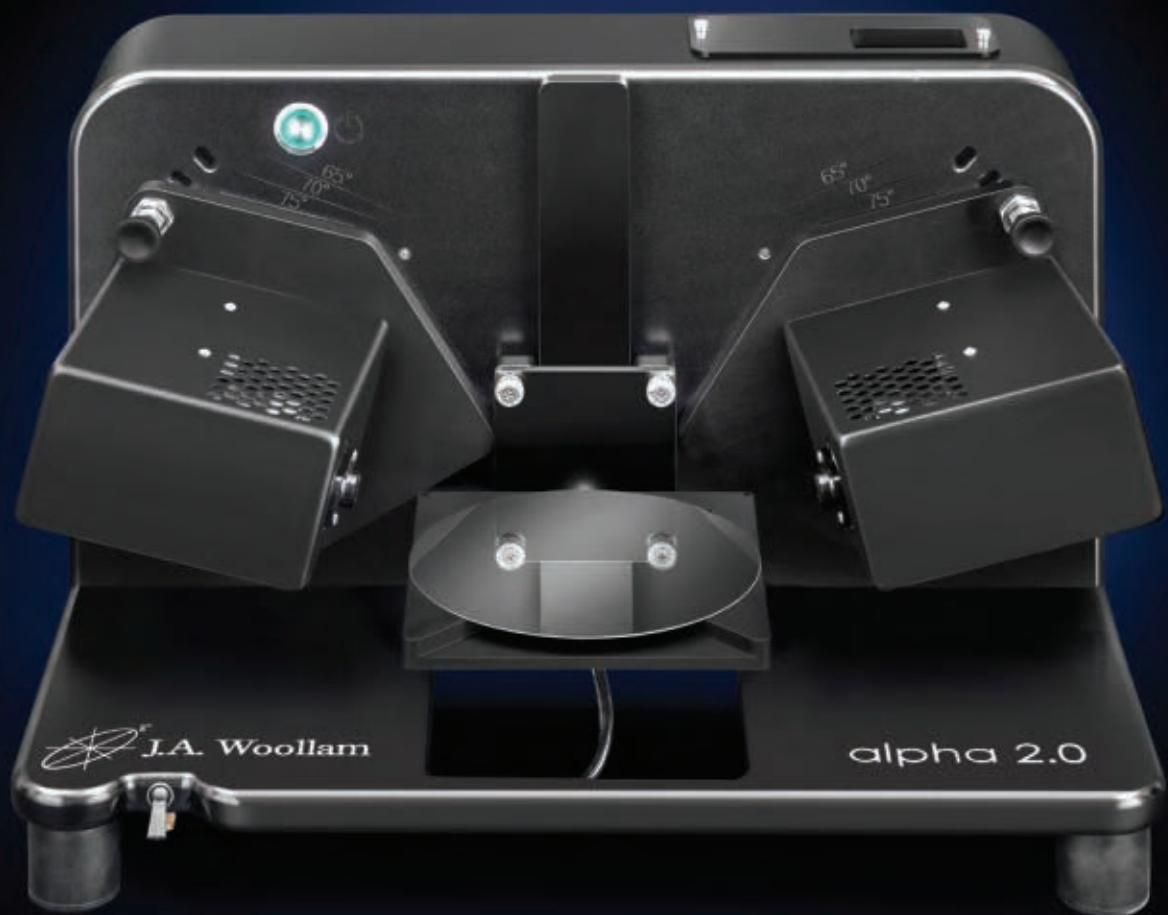
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# Putting a return to the Moon in perspective



**THE CREW OF ARTEMIS 2** at NASA's Kennedy Space Center. The mission aims to take humans to the Moon for the first time in decades. (Courtesy of NASA/Kim Shiflett.)

The article “Back to the Moon . . . to stay?” by Michael J. Neufeld in the December 2023 issue of PHYSICS TODAY (page 40) presents a great deal of information many people outside the science and technology communities should be aware of.

Neufeld writes, “Public enthusiasm for sending astronauts to the Moon has remained weak—only 12% of respondents in a recent poll chose it as one of the ‘top priorities’ for NASA (monitoring asteroid threats got 60% and Earth’s climate 50%).” In my experience in doing public outreach about space exploration, I have found few people who can answer correctly when asked what the distance from Earth to the Moon is or how many people have spent time on our natural satellite. Those types of questions should be included in any poll on support for lunar exploration.

Included in Neufeld’s article is a histogram of NASA funding from 1958

through 2020 as a percentage of the federal budget. Note, though, that roughly every 10 days the US spends on national defense the equivalent of the NASA budget for the entire year.<sup>1</sup>

Neufeld mentions those who have pushed for the use of robotic spacecraft because of the decreased costs and danger involved. But Steven Squyres, principal investigator for the science payload on the Mars rovers *Spirit* and *Opportunity*, commented in 2005, “What we have done with these rovers a really good pair of field geologists could have done in a long weekend.”<sup>2</sup>

As Neufeld points out, there are challenges, such as the effects of harsh radiation and low gravity, that need to be overcome for humans to adapt to space. But solving challenges is what science and engineering is about. Neufeld concludes by writing, “We are going back to the Moon to stay, at least for a while—and maybe for the long term.” I look

forward to gazing up at the Moon and knowing the names of the people who are living and working there.

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2. S. Squyres, *Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet*, <https://www.c-span.org/video/?188724-1/roving-mars-spirit-opportunity-exploration-red-planet> (11 August 2005).

Frank Lock

(lockphys@gmail.com)  
Gainesville, Georgia

## Reconsidering tenure

The article “When tenure fails” by Toni Feder (PHYSICS TODAY, October 2023, page 44) points to the need for academia to consider whether the tenure system needs revamping. Of course, any

demanding role needs a thorough selection process. But we must weigh its costs and benefits. In tenure's case, the benefits can include a high quality of research and teaching. The costs include the stress applicants face and the significant faculty resources that go into the tenure review. Not to mention, the outcome of that review can be largely arbitrary, as noted in Feder's article by Meg Urry, director of the Yale Center for Astronomy and Astrophysics, who has observed the tenure system for 40 years.

The UK stopped using the tenure system in the late 1980s. Newly hired lecturers typically have a probationary period with some strings attached, such as requirements to graduate from a teaching course or to submit a certain number of large grant applications (but not necessarily win them, since that is beyond applicants' control). The requirements are much less stringent than those of the US tenure system. The lecturer-selection panels I have sat on have all agreed that the current level of competition and the quality of short-listed candidates are so high that appointed lecturers are almost guaranteed to be successful. Of course, sometimes things go wrong in ways we cannot foresee, but that risk is too small to worry about.

Without a tenure system, the UK is still successful in terms of research output. According to a 2019 UK government report comparing the research output of many countries, the UK had the highest field-weighted citation impact. It was also the country from which publications are most likely to be highly cited.<sup>1</sup>

It would be interesting to see whether different outputs related to physics in particular are correlated with the tenure system. Armed with this evidence, physicists could lead the way in improving faculty-hiring processes.

Feder reports that current academic

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practices have resulted in assistant professors receiving the advice to keep their research "mainstream." We should consider such a system problematic, as it stalls progress and is at odds with what research is about.

Feder also notes that "an unwritten requirement" for tenure "is that a candidate be a 'good fit.'" It is unclear what "fit" means exactly, but we can assume that it means to be like others both professionally and socially. Fitting has not been discussed at the panels I have been a part of, but I can imagine that the issue exists outside the US tenure system. I can think of many ways in which being different, and not fitting, is positive and contributes to versatility. That also goes well with the recent "bin the boffin" initiative led by the Institute of Physics in the UK.<sup>2</sup> There clearly will be cases when not fitting is a problem. We need to have tools to deal with such cases, and we often do. And in my and my colleagues' experience, dealing with those cases has often been easier than dealing with issues created by those who "fit."

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2. Institute of Physics, "IOP's Bin the Boffin campaign lights up media London," (29 June 2023).

Kostya Trachenko

([k.trachenko@qmul.ac.uk](mailto:k.trachenko@qmul.ac.uk))

Queen Mary University of London

London, UK

## Tidal power's limits

In the August 2023 issue of PHYSICS TODAY (page 22), Rachel Berkowitz nicely examines how turbines installed in strong tidal currents could provide power for small communities that currently rely on diesel generators. The article emphasizes the reliability and predictability of tidal energy compared with solar and wind power. Unfortunately, tidal power is limited at the global scale and cannot contribute significantly to humanity's overall needs.

To illustrate this point, compare current human power consumption of about 20 terawatts (TW) with the availability of

various renewable energy sources. Insolation at Earth's surface is approximately 100 000 TW, showing the potential of solar power. Wind power, with dissipation of close to 1000 TW, also has potential. Tidal dissipation is a mere 3.7 TW. Simple models indicate that this is a reasonable upper bound to what could be extracted in principle, though extracting more than a small amount is not technically feasible and would cause significant changes in global tides as well as major changes locally.

Places such as Cook Inlet in Alaska, the Bay of Fundy in Canada, Pentland Firth north of Scotland, and Cook Strait in New Zealand offer a potential of hundreds of megawatts or even more than a gigawatt (GW), but a strong current of, say, 3 m/s corresponds to a head of only 0.5 m. Providing significant amounts of power in such a situation requires huge fluxes of water through turbines—several tens of thousands of cubic meters per second per GW, depending on the details of the installation. A large turbine array would also slow the flow, which would limit the available power and potentially have a significant environmental impact. In places where the strong current is associated with a tidal range of several meters, exploitation using a barrage or lagoon seems preferable, although this would have other disadvantages.

Instead, the best energy-related use of strong, cold tidal currents might be to provide cooling water for nuclear reactors. For example, in the Bay of Fundy, which has the world's highest tides and where the use of tidal turbines is proposed, a CANDU-6 pressurized heavy-water reactor at Point Lepreau uses 26 cubic meters per second of cooling water for a power output of up to an average 600 MW of electricity. That's just 43 cubic meters per second per GW, less than the tens of thousands of cubic meters per second required for the same output using in-stream turbines. Many factors need to be taken into account in comparing potential sources of power but, even where a large-scale in-stream tidal-power project is feasible, it seems appropriate to quote the late David MacKay's freely available book *Sustainable Energy—Without the Hot Air*: "Please don't get me wrong: I'm not trying to be pro-nuclear. I'm just pro-arithmetic."

Chris Garrett

([cgarrett@uvic.ca](mailto:cgarrett@uvic.ca))

University of Victoria  
British Columbia, Canada

# Bubble lasers can be sturdy and sensitive

Made of liquid-crystal films, the soft, air-filled lasers have stable spectra that shift when the bubbles are squeezed.

**S**oap-bubble physics is nearly as broad as physics itself. Bubbles are an inexpensive, versatile platform for studying effects in fields such as fluid dynamics, optics, and even granular flow. (See, for example, PHYSICS TODAY, July 2019, pages 16 and 68.) Now Zala Korenjak and her PhD adviser Matjaž Humar, of the Jožef Stefan Institute in Ljubljana, Slovenia, report a surprising new addition to that already impressive resumé: An ordinary soap bubble makes a pretty good laser.<sup>1</sup>

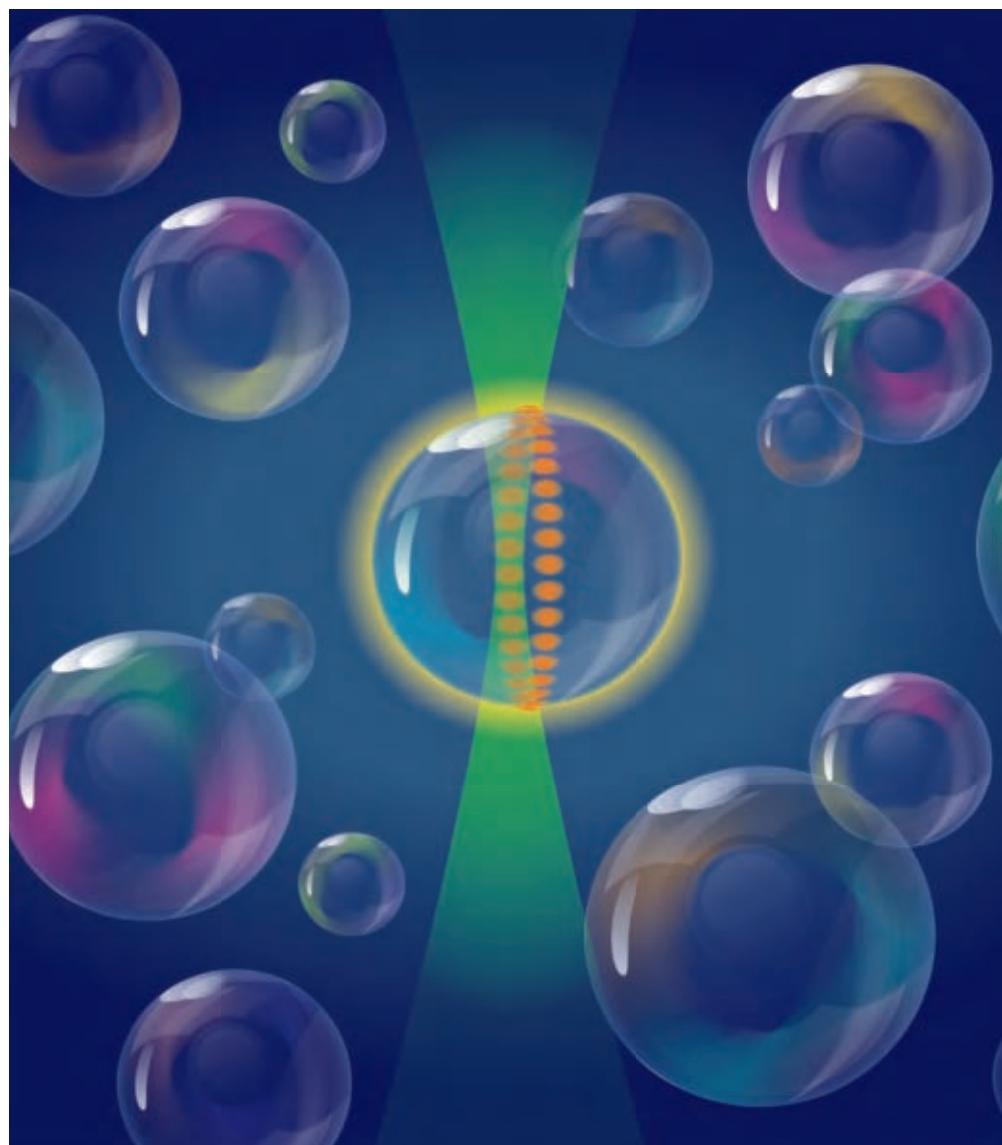
Lasers amplify light by passing it repeatedly through a gain medium, usually by bouncing it between a pair of mirrors. In a soap-bubble laser, the bubble itself serves as an optical resonator. Light waves bounce around and around the bubble's surface at resonant frequencies called whispering-gallery modes (WGMs; one is illustrated by the orange dots in figure 1). The name comes from a similar acoustic effect discovered in the whispering gallery in the dome of St Paul's Cathedral in London.

WGM lasers that use ring-, tube-, or sphere-shaped glass resonators are nothing new, and Humar and his group were already working with them in other contexts. But the soap-bubble version is striking in its low-tech simplicity. And because the bubble is soft and filled with air, it's sensitive to its environment in ways that more conventional lasers aren't.

Korenjak and Humar found their most promising results when they switched from soap to another type of bubble, made of so-called smectic liquid crystal. Smectic bubbles are not nearly as prone to bursting as soap bubbles are, and their stability and uniform thickness are a boon to their optical properties.

## Soap shells

"These experiments could have been done 30 years ago, easily," says Humar. "We were quite surprised that nobody

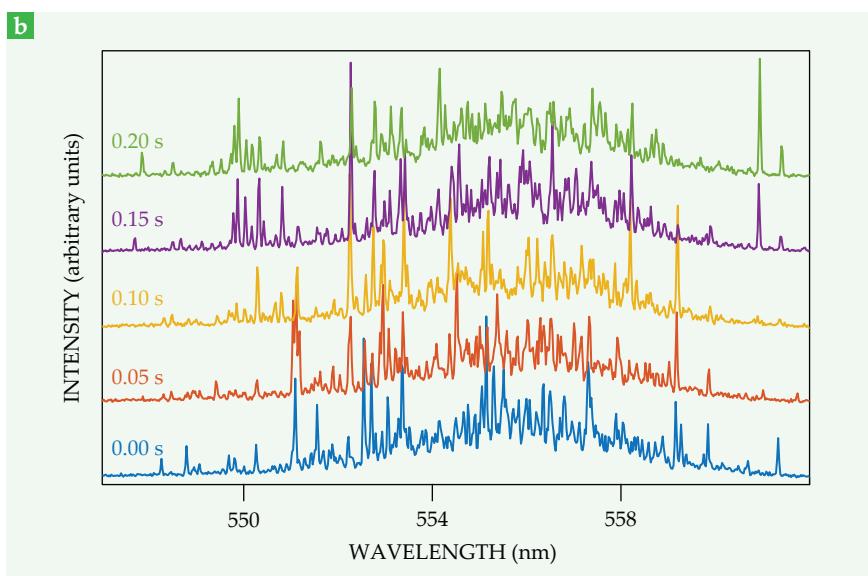
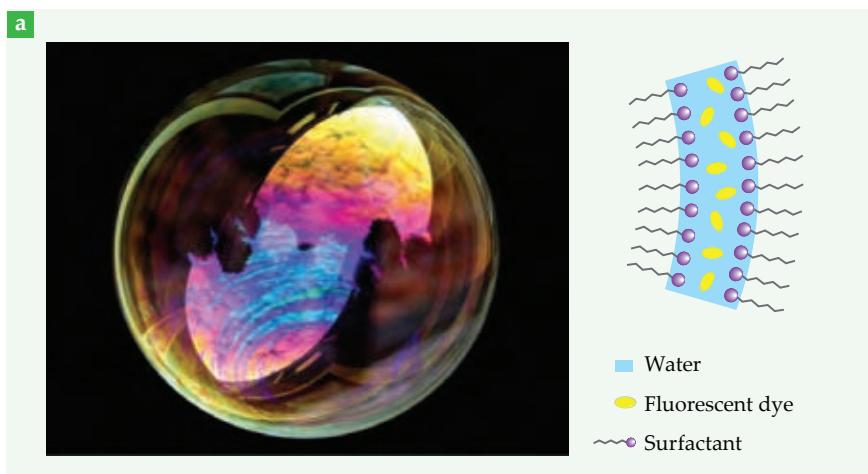


**FIGURE 1. WHISPERING-GALLERY MODES (WGMs)**, such as the one illustrated in orange, are central to a bubble's optical properties. When a bubble is doped with laser dye and pumped with an external laser (green), the bubble lases at the WGM frequencies. (Courtesy of Zala Korenjak and Matjaž Humar.)

had tried this before." All it took was the right inspiration, which for Humar came from a 2020 paper by Mordechai Segev, Miguel Bandres, and colleagues on laser beams in soap films.<sup>2</sup>

Plenty of analysis has been done on how light bounces off soap bubbles: Thin-film interference, combined with variations in the film thickness, creates the colorful swirling iridescence seen in

figure 2a. In contrast, Segev, Bandres, and colleagues looked at how light propagates inside a soap film—in effect, treating the film as a 2D waveguide. They found that those same thickness variations focused and split the laser beam to produce an effect called branched flow. (See the article by Eric Heller, Ragnar Fleischmann, and Tobias Kramer, PHYSICS TODAY, December 2021, page 44.)



**FIGURE 2. A SOAP BUBBLE** consists of two layers of surfactant molecules enclosing a layer of free-flowing water. (a) Because the water layer's thickness is close to optical wavelengths and varies over the surface of the bubble, thin-film interference gives rise to the characteristic iridescent appearance. (b) A soap-bubble laser's whispering-gallery-mode spectrum, which is sensitive to the bubble's thickness, changes erratically from moment to moment. (Bubble photo courtesy of Brocken Inaglory/Wikimedia Commons/CC BY-SA 3.0 DEED; schematic and spectrum adapted from ref. 1.)

"I wondered if the bubble itself could be the laser," says Humar, and he tasked Korenjak with finding out. "I thought it would be a fun student project. But it turned out that we got some really good results."

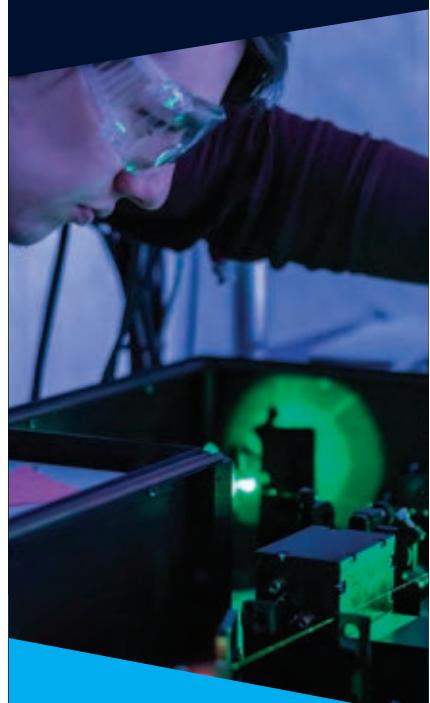
All it took was dissolving a few specks of laser dye in the soap solution and shining a pump laser on the resulting bubbles. Pumped dye lasers are a common setup in laboratory experiments that require wavelength-tunable output. The fixed-wavelength pump laser excites the dye molecules, which then emit light at a longer wavelength. When a molecule

by chance emits a photon into a resonant laser-cavity mode—for the bubble, a WGM—it stimulates other molecules to emit more and more matching photons. The result: laser light.

Dye molecules can emit light across a range of wavelengths. To tune the output to a desired wavelength, a conventional dye laser uses a diffraction grating to scatter all other wavelengths out of the laser cavity. There's no place to put a diffraction grating in a soap-bubble laser, so the bubbles lase simultaneously at all the WGMs across the dye's emission spectrum. But just because the bubbles'

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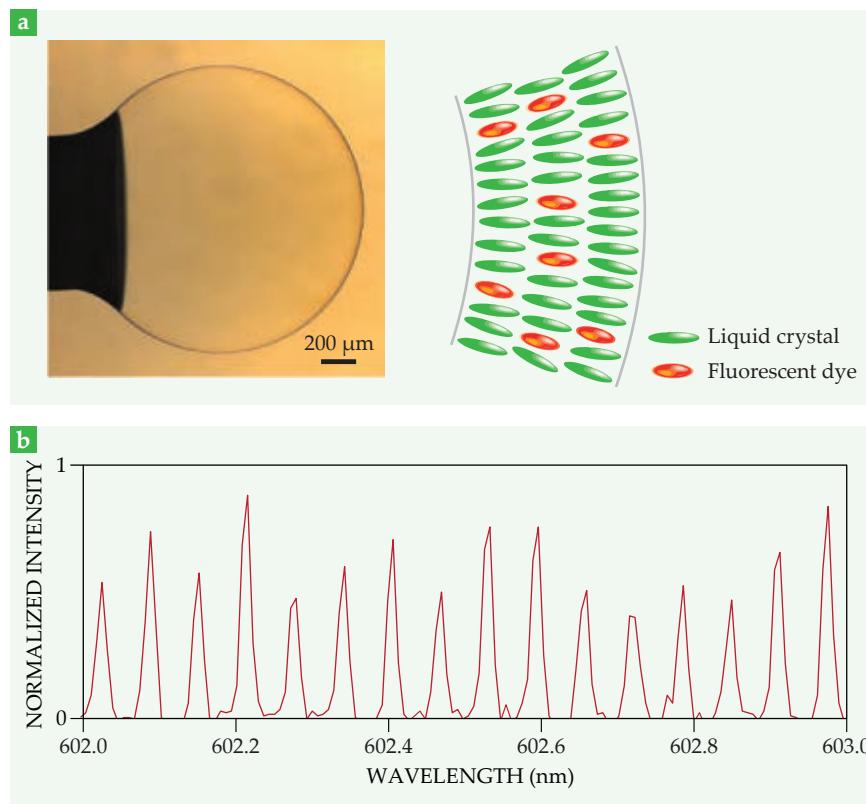
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**FIGURE 3. A SMECTIC BUBBLE** is thinner and more uniform than a soap bubble. (a) The bubble is made of organic liquid-crystal molecules that arrange themselves into ordered layers. (b) As a result, a smectic-bubble laser lases with a stable spectrum of evenly spaced modes. (Adapted from ref. 1.)

output isn't monochromatic doesn't mean they're not lasers.

The soap-bubble WGM spectrum, however, is erratic and hard to interpret. Roughly speaking, a spherical resonator's WGMs are those wavelengths for which a whole number of light waves fit around the sphere's circumference. But when the resonator is a thin spherical shell—a bubble—the picture becomes more complicated. The light interferes with itself as it bounces between the bubble's inner and outer surfaces. The interference can be described as a thickness-dependent effective refractive index, which affects how many wavelengths fit around the circumference.

And a soap bubble's thickness is always changing. As shown in the schematic in figure 2a, the film consists of two layers of soap molecules with freely flowing water in between. The flow of water, driven by variations in surface tension, gives rise to the characteristic swirling iridescence. It also creates a complicated, dynamic lasing spectrum, as shown in figure 2b.

"It was a nice surprise that the laser works with just soap," says Humar. But in search of a more stable lasing spectrum, he and Korenjak turned from soap bubbles to smectic bubbles.

### Liquid-crystal layers

A smectic film, as shown in figure 3a, contains no water. It's made entirely of organic liquid-crystal molecules—plus, in Humar and Korenjak's experiments, a little laser dye. Because there's no water, the liquid doesn't inevitably drain from the top of the bubble to the bottom, and smectic bubbles can last for tens of minutes without bursting.

Smectic liquid-crystal molecules arrange themselves into orderly layers, and the number of layers in a smectic bubble is the same everywhere. The result is a bubble that's eerily transparent, with no iridescence to be seen. But, as shown in figure 3b, it lases with a beautifully regimented spectrum of equally spaced WGMs.

Because the WGM spacing is directly related to the bubble circumference, the

lasing spectrum offers a quick and precise way to track the bubble size and, in turn, the ambient pressure. Plenty of pressure-sensing technologies exist already, but most are optimized for detecting either small pressure changes or large ones. Korenjak and Humar estimate that their smectic bubbles should be capable of both: A freestanding bubble could measure pressures up to 10 000 kPa—that's 100 times atmospheric pressure—while being sensitive to pressure changes as small as 1.5 Pa.

But most of the researchers' experiments weren't performed on freestanding bubbles. Annoyingly, because smectic films are so thin—just tens of nanometers, compared with hundreds of nanometers for soap bubbles—smectic bubbles steadily leak air over time. To keep a bubble from collapsing entirely, Korenjak and Humar leave it attached to a capillary (one is shown in figure 3a) so they can reinflate it as needed.

The capillary makes a big difference to the pressure sensitivity. The air in the bubble and in the capillary get compressed at the same time, so it takes a smaller change in external pressure to measurably alter the bubble's size. The exact response depends on the volume of the capillary and the bubble, but the net effect is to shift the whole dynamic range downward: The bubble is sensitive to even smaller changes in pressure, but it can no longer withstand such large ones.

Korenjak and Humar were focused on basic research rather than developing a practical technology. "But I imagine that this could be used in a specialized application where you really need a huge dynamic range," says Humar. "You probably wouldn't want to use it in consumer products, like your phone. But for something like aerospace, maybe."

Since sound waves are just pressure oscillations, the researchers are now exploring whether smectic-bubble lasers can work as microphones. They haven't yet tried recording complicated waveforms, such as people's voices. But they can distinguish low-volume tones of different frequencies.

**Johanna Miller**

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# How a mineral that's always wet gets wetter

Potassium-rich feldspar is a hydrophilic mineral that accelerates ice nucleation in the atmosphere. For the first time, the atomic surface structure has been observed.

In the quest to understand cloud formation, one mineral has been a central point of curiosity. Microcline is a potassium-rich type of feldspar, a class of minerals that accounts for 60% of Earth's crust. More importantly for clouds, ice nucleation occurs unusually easily around microcline—and atmospheric scientists don't know why.

Ice nucleation doesn't necessarily happen at the mineral's surface, but to solve the mystery, researchers still needed to see what the atomic structure looked like at the surface. Researchers led by Ulrike Diebold of the Technical University of Vienna used a new technique to prepare their sample for microscopy.<sup>1</sup> They found a honeycomb pattern of aluminum and silicon surrounding potassium ions that aligned with expectations of the field. Angelika Kühnle of Bielefeld University in Germany and colleagues found similar results using a different preparation technique.<sup>2</sup> The two groups' findings are an important stepping stone in understanding the complexities of ice nucleation on feldspar. The experiments also revealed that it is difficult to keep the mineral dry for imaging.

## Break through the rock

For ice to form in the atmosphere, water molecules must first assemble into a seed crystal, a process called nucleation. Water molecules can be attracted to atmospheric particulates of minerals, which facilitate that mode of ice nucleation. Many different minerals can help create ice clouds, but potassium feldspar—and microcline in particular—stands out. Ice nucleation on microcline has been observed to begin in environments approximately 20 K warmer than on most other minerals.<sup>3</sup>

Previous experimental research has been limited to studying the mineral's macroscopic properties. Prior to Diebold and Kühnle's studies, the role of the sur-



**POTASSIUM-RICH FELDSPAR** is a common mineral that significantly contributes to atmospheric ice nucleation. The mineral exhibits preferential cleavage planes, conveniently creating a flat surface to study at the atomic level. (Image by iStock/FokinOl.)

face chemistry—the details of the surface at the atomic scale and its reactivity with water—had not previously been explored experimentally. Atomic force microscopy (AFM) is a tool that can map the surface with atomic resolution and determine whether there's any surface reconstruction, the rearrangement of atoms into a structure different from that of the bulk. It is its sensitivity to short-range forces that enables AFM to achieve atomic resolution. But obtaining a clear image is hard when the surface is wet or otherwise not atomically flat. (For more on AFM, see the article by Daniel Rugar and Paul Hansma, PHYSICS TODAY, October 1990, page 23.)

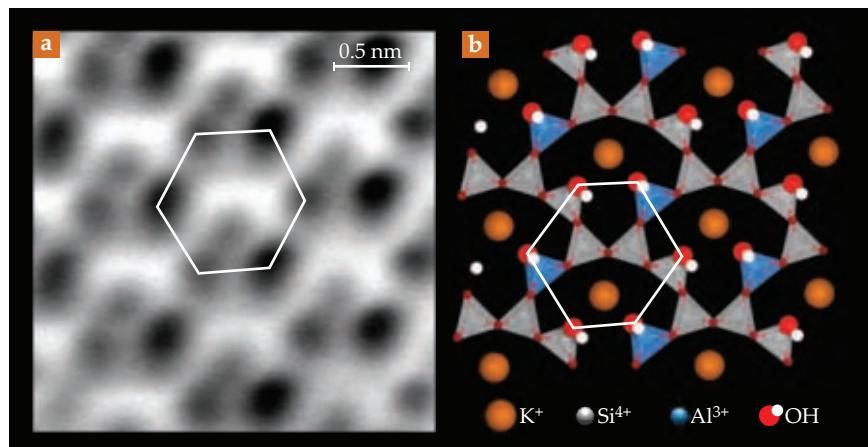
To prepare the sample for study, Diebold's team put microcline in a UHV chamber, which prevents any contamination from reaching the surface after its preparation. The rock is then cleaved, exposing a pristine, dry surface. The splitting creates a strong charge at the surface, which interferes with the AFM measurement. Traditionally, the sample is annealed to dissipate the charge—that was the method chosen by Kühnle and her colleagues in their study of the mineral. On the other hand, Diebold's group used a technique they had tried for the first time in a study published just last

year: irradiating the sample with x rays.<sup>4</sup> Each group independently studied the atomic surface structure of microcline, and both were met by the same initial surprise: The sample was immediately wet.

## Just add water

"At the beginning it was really confusing," says Giada Franceschi, a postdoc who coordinated the project in Vienna. "Because we were breaking the material apart, you would think the surface should be dry; we have such a perfect vacuum." Multiple experiments confirmed that the sudden moisture on the surface wasn't a fluke. Franceschi traced the hydroxyl groups to water that had been released from inside the rock when the sample was cleaved. The small amount of water was enough to immediately coat the mineral's surface.

Although the surfaces were wet, both research groups were still able to use AFM to determine the underlying atomic structure of the microcline surface. The images showed that the mineral did not exhibit surface reconstruction. Al and Si atoms bound to OH groups surrounded the potassium ions in a regular, buckled honeycomb pattern. Franziska Sabath, a postdoc working with Kühnle, took the experiment



**POTASSIUM FELDSPAR'S SURFACE** was observed by researchers at both the Technical University of Vienna and Bielefeld University in Germany. (a) Atomic force microscopy revealed the hexagonal structure connecting aluminum hydroxyl groups (darkest dots) to the silicon hydroxyl groups. The groups' experiments confirmed predictions based on the bulk material structure. (b) A diagram of the observed structure: aluminum atoms and silicon atoms bonded to hydroxyl groups, with gaps filled in by potassium ions. (Adapted from ref. 1.)

one step further, imaging microcline with multiple layers of water molecules to get a 3D perspective of the interface between the solid and the liquid. "The first layer of water is really strongly

bound, and the other layers are really mobile," she says. Sabath suspects that the ease of ice nucleation could be attributed to how the initial layer of OH groups connects to both the surface

structure and the next layers of water, although details of the flat surface studied in the current work likely differ.

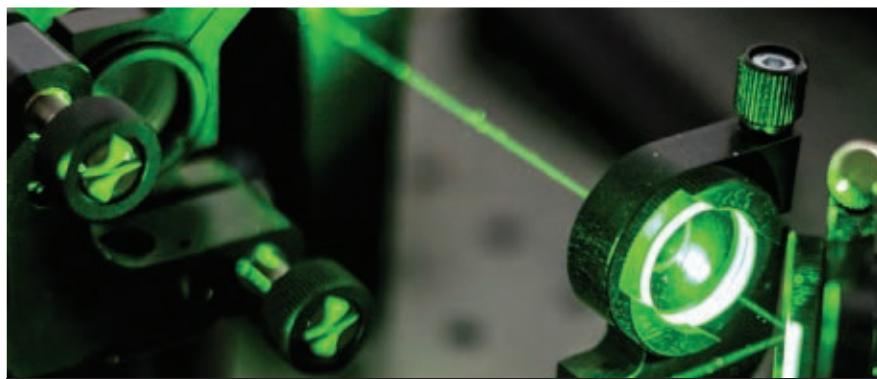
Although the immediate addition of OH groups to the surface was unexpected—the researchers were surprised to see how little water was needed to hydroxylate the surface—the rapid bonding of OH groups did align with what atmospheric scientists expect happens in nature. Dust particles in the atmosphere are surrounded by water and would also start from a hydroxylated state before any ice nucleation occurred. Establishing the pattern of the water bonds on the surface will improve the ability of atmospheric scientists to model the nucleation process and give them greater confidence in their simulations.

### Atomic ordering

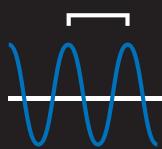
Determining the surface structure of microcline is only the first step to understanding ice nucleation on microcline. Ice nucleation requires more than an initial layer of water, and atmospheric particles are much smaller than lab samples. Sabath says she hopes to obtain a precise 3D structure of multiple layers of water on a surface with step-like defects.

Knowing the surface structure doesn't completely solve the mystery of why microcline is so efficient at ice nucleation, but Franceschi thinks it might be a significant part of the story. As more water interacts with the surface, it encounters the Al-OH and Si-OH groups that have naturally formed bonds in specific orientations. "We think that the arrangement of these OH groups is really important to bind water in a precise way and then make periodic ice structures in the long term," Franceschi says. The Vienna group is now studying other minerals that are less effective at ice nucleation; initial findings are showing a more disordered arrangement of hydroxyl groups.

Jennifer Sieben



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## Green ammonia can be a clean energy source

The world's second-most-produced chemical is poised to grow beyond its use in fertilizers to become an efficient medium to carry green hydrogen across the oceans.

As most of the world strives to attain net-zero carbon dioxide emissions by mid century, no fuel is cleaner than hydrogen produced with renewable energy. But hydrogen has a low energy content—just one-tenth that of natural gas at ambient temperature and pressure and one-sixth in liquid form. Ammonia packs more energy per molecule, and it's getting attention for its potential to carry hydrogen—and hence carbon-free energy. Liquid ammonia stores much more hydrogen than liquid hydrogen: 121 kg per m<sup>3</sup>, compared with 71 kg per m<sup>3</sup>. And liquefying ammonia is far easier and consumes much less energy.

Ammonia, however, must first solve its own carbon problem. Synthesis by the conventional process is a major contributor to climate change, accounting for 620 million tons of CO<sub>2</sub> each year, about 1.3% of annual global anthropogenic emissions of the greenhouse gas, according to the International Energy Agency (IEA). Nearly all of the approximately 200 million tons of ammonia produced annually by that process is so-called gray ammonia. It originates with hydrogen that is steam-reformed from natural gas or coal and leaves CO<sub>2</sub> as the byproduct. The atmosphere provides ammonia's nitrogen content.

Substantial reductions in CO<sub>2</sub> emissions would be achieved if the greenhouse gas were to be captured and stored—the so-called blue-ammonia method. Green ammonia—manufactured entirely without hydrocarbons—obtains its hydrogen from splitting water in electrolyzers pow-



**A PROTOTYPE** ammonia-powered ship engine built by MAN Energy Solutions. The company is now building a commercial engine for a Japanese shipbuilder.

ered by renewable electricity. Adding 10 electrolyzers of 30 MW each per month and one large carbon capture and storage plant every four months between now and 2050 would reduce emissions from ammonia production by only 70%, according to the IEA. Near-zero emissions from ammonia production would require even more rapid deployment of blue and green technologies, the agency says.

Hydrolysis is a mature technology and is widely available. But green hydrogen, the component of ammonia made with hydrolysis, is more costly than the hydrogen produced with blue or gray methods. Depending on the cost of electricity where it's produced, green hydrogen ranges from \$4.50/kg to \$12/kg, according to an August 2023 report from BloombergNEF. Gray hydrogen ranges from \$0.98/kg to \$2.93/kg, and blue, from \$1.80/kg to \$4.70/kg. The US Department of Energy has set a goal for green hydrogen to fall to \$1/kg by 2031, the point at which it would become competitive with blue or gray.

"Green hydrogen deployed at manufacturing scale would enable all sorts of technological advancements for green chemicals, ammonia among them. Ammo-

nia is an obvious fit," says Nicholas Thorneburg, senior reaction engineer at the National Renewable Energy Laboratory. But green ammonia is not mature enough for industrial-scale manufacturing, he says.

Sameer Parvathikar, director of renewable energy and energy storage at RTI International, says the cost competitiveness of green ammonia is highly dependent on location. His modeling has indicated that green ammonia produced at a small scale in three Minnesota counties already competes with gray, even without subsidies. Using green ammonia as an energy source could provide a buffer between intermittent wind and solar energy sources and the more constant demand for electricity, he says, noting that ammonia is far easier to store than hydrogen. With funding from DOE's Advanced Research Projects Agency-Energy, RTI and its partner organizations are building a portable green-ammonia synthesis plant adjacent to wind and solar farms.

### A carrier of energy

Today, about 70% of ammonia is used in the manufacture of fertilizer; the rest goes to various industrial applications.

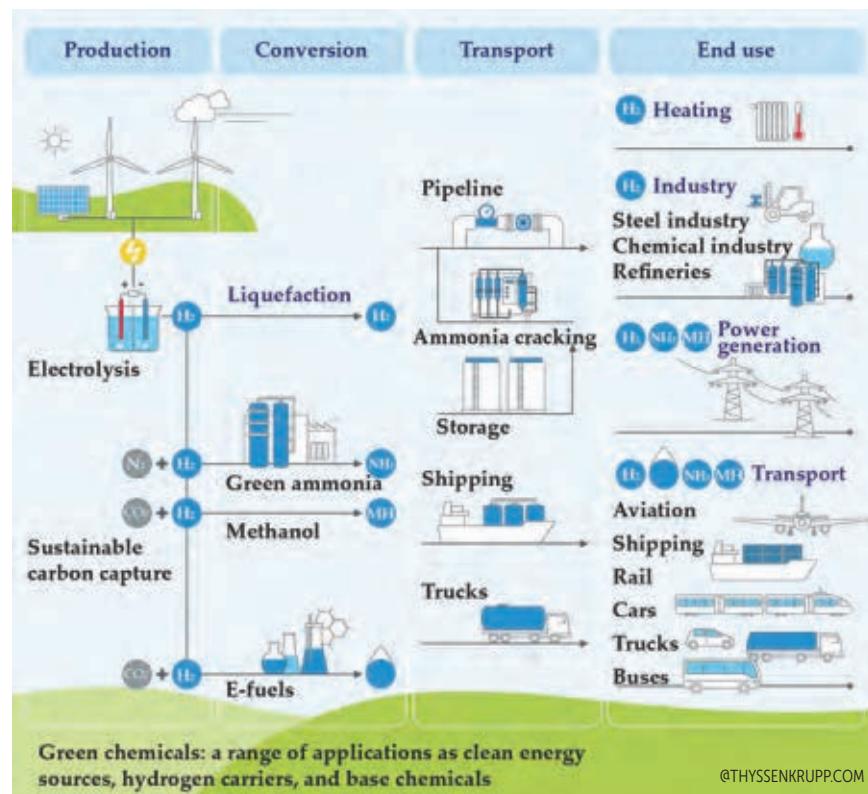
Ammonia can produce energy through direct combustion. Alternatively, once its hydrogen is separated from the nitrogen—by a process known as cracking—it could power many types of fuel cells, including the polymer-electrolyte membrane found in most vehicle applications. Steelmaking, refineries, and chemical plants can also be decarbonized with hydrogen cracked from ammonia. Most fuel-cell types cannot accept ammonia directly; solid-oxide fuel cells can, but they are impractical for mobile and other intermittent applications because of their high operating temperatures of 400–600 °C, notes Thornburg.

Australia, Brazil, India, and South Africa are among the nations that aspire to become suppliers of green hydrogen. On the demand side, energy-poor Japan and South Korea are striving to decarbonize their economies. Hydrogen, though, is not easily transportable by ship. Cooling it to a liquid is highly energy intensive, and much of the liquid will boil off during transit. Ammonia, on the other hand, has long been moved across oceans.

Green-ammonia exports are expected to surge from virtually none today to 121 million tons per year by 2050, says a report from Rystad Energy, a Norway-based market forecasting firm. If announced projects are completed, African nations will generate the most exports, with 41 million tons, followed by Australia with 36 million tons, the report says. Existing liquefied petroleum gas (LPG) terminals in ports could readily be converted to handle ammonia, but there are far too few of them to handle the anticipated demand. Australia currently has seven ammonia terminals and a storage capacity of 173 000 tons. That would accommodate just two to three days of proposed clean-ammonia exports, according to Rystad.

Around 200 very large carriers would be needed to meet the projected 2050 green-ammonia demand, requiring an investment of \$20 billion. Rystad cites growing interest in retrofitting some of the globe's 1500 LPG carriers to transport ammonia.

"Ammonia has a very established supply chain, and hydrogen's supply chain isn't global, only regional," says Thornburg. "So ammonia has some head starts as a favorable solution. It could also be a bridge solution, used for a couple decades as a hydrogen economy



**AMMONIA** made with power from renewable-energy sources is likely to transport the hydrogen needed for a clean-energy future. Other candidates to serve as hydrogen carriers, including methanol and other reversible hydrocarbons, are low carbon but not CO<sub>2</sub>-emissions-free.

grows, and then phased out if there are more compelling solutions."

Europe, keen to shed its dependence on Russian natural gas, is looking to ammonia to meet some of its energy needs. In 2022 Germany unveiled a €900 million (\$970 million) tender for green hydrogen to be imported from outside the European Union. That prompted oil giant BP to announce plans to build a green-ammonia terminal at the port of Wilhelmshaven, Germany. Up to 130 000 tons per year could be imported and cracked to hydrogen there. The derived hydrogen would be fed into a distribution-pipeline network to which Germany has committed €20 billion to build. Meanwhile, the Japanese electricity producer JERA in 2022 initiated a tender for an annual supply of 500 000 tons of green ammonia, with deliveries set to begin in 2027.

JERA initially plans to crack the ammonia and blend the hydrogen into the natural gas fuel at a single power station, lowering its CO<sub>2</sub> output.

In the US the DOE last October selected seven regional hydrogen hubs to

share \$7 billion in hopes of stimulating a domestic energy market for green hydrogen. Green-ammonia production is included in the plans of at least one of them, the Heartland hub to be located in the Dakotas and Minnesota.

An IEA report issued in 2021 concluded that producing and transporting ammonia over long distances would be cheaper than shipping liquefied hydrogen: \$14–\$27/GJ for ammonia and \$22–\$35/GJ for hydrogen. A 2021 study by Sudipta Chatterjee, Rajesh Kumar Parsapur, and Kuo-Wei Huang, however, found that for fuel cells, the need for cracking could limit ammonia's economics. Cracking consumes about 46 kJ per mole of ammonia, says Thornburg. "It's not an insanely high energy barrier," he says. It's far less than the 804 kJ per mole required to strip hydrogen from natural gas.

National Renewable Energy Laboratory scientists are nonetheless exploring less-energy-intensive cracking technologies such as photochemistry and auto-thermal reforming, which couple the endothermic ammonia-dissociation re-

action with the heat from the exothermic oxidative ammonia-reforming reaction.

## Shipping Potential

A prime candidate market for green ammonia is maritime shipping, which experts say will be one of the most difficult industries to decarbonize. The 33 000 merchant vessels that ply the high seas belch out around 1 billion tons of  $\text{CO}_2$  each year, about 3% of the global total, according to the International Maritime Organization, the United Nations agency that oversees shipping. That's equivalent to the emissions from all passenger vehicles in the US. Nearly all ships today burn heavy fuel oil in their hulking two-cycle engines, says Nikolaos Kourtidis, principal promotion manager and business developer for dual-fuel engines at Denmark's MAN Energy Solutions. MAN engines power around 23 000 merchant ships.

Shipowners today are starting to order dual-fuel vessels, which are capable of burning LPG and other hydrocarbons such as biogas and methanol in addition to fuel oil; about half of MAN's 2760 total marine-engine orders are dual fuel, Kourtidis says. While dual-fuel engines can be retrofitted to burn ammonia, they are not optimized for it, he says. MAN is supplying a purpose-built ammonia-fueled engine for a shipbuilder in Japan. Its maiden voyage will be in late 2025 or early 2026, aboard the world's first ammonia-powered ship, he says.

Other collaborations have said that they will be first with an ammonia-powered ship. Those include ventures headed by Norway-based companies NCE Maritime Cleantech and Yara International, a major ammonia producer.

Shipowners are expected to initially switch to methanol and, to a lesser extent, LPG to lower their emissions. MAN expects ammonia to become a significant player beginning around 2035 and to become the most widely used fuel by 2050. Methanol is expected to rise in tandem with ammonia to around 26% of the total fuel mix, just ahead of fuel oil, which will fall to a 20% share by mid century, according to MAN's outlook.

## Special considerations

Ammonia could also be blended into fuel oil to lighten a ship's carbon footprint. Because it ignites at a higher temperature

and higher pressure than fuel oil, burning a fuel mix with more than 50% ammonia will require engine components that can handle those conditions. Kourtidis says MAN's ammonia-engine design has combustion chambers with a geometry designed specifically for ammonia.

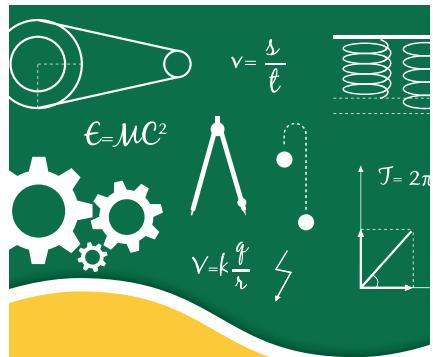
Because of its higher ignition temperature, ammonia requires a pilot fuel—about 5% of the total volume—to initiate combustion. That could be methane or another hydrocarbon. It could also be hydrogen supplied by cracking some of the ammonia on board the ship, notes John Steelman, deputy director of the transportation-decarbonization program at the Clean Air Task Force, a Boston-based nonprofit.

An ammonia-fueled vessel would require three times as much onboard fuel storage as fuel oil. That's more than a small consideration for a seagoing ship that burns 100–200 tons of fuel oil each day, notes Kourtidis. Ammonia's toxicity—high exposures in the blood can cause convulsions—also mandates more safety measures than those needed for fossil fuels, adding further to capital requirements.

Ammonia combustion emits oxides of nitrogen, which are far more potent greenhouse gases than  $\text{CO}_2$ . Nitrous oxide, for example, has 265 times as much greenhouse effect per unit mass as  $\text{CO}_2$  and lasts for more than 100 years in the atmosphere. Ships are already equipped with selective-catalytic-reduction devices that can remove around 80% of those emissions. R&D is underway to further reduce maritime pollution of oxides of nitrogen, says Steelman.

Regulating or imposing a price on carbon emissions will encourage the adoption of low-carbon fuels and ammonia to power ships. That is happening in the European Union, where beginning next year, vessels that move between its ports will be required to reduce their greenhouse gas emissions by an initial 2% and reaching 80% by 2050. The International Maritime Organization has called for a minimum 20% reduction in total maritime greenhouse gas emissions by 2030, and at least 70% by 2040. With the anticipated increase in the volume of trade during that period, individual ships will need to cut emissions by more than 90%, according to the Global Maritime Forum, an industry trade group.

David Kramer



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# NASA unveils a supersonic plane with a quiet boom

A simple concept, a sophisticated process: Reshape contours to prevent coalescence of shock waves.

A plane first surpassed the speed of sound in 1947. Now, more than three-quarters of a century later, NASA aims to do it again, but this time quietly. When a plane flies faster than the speed of sound—about 1100 km/h at typical flying altitudes and atmospheric conditions—the resulting shock waves create a signature double boom. The explosion-like noise can scare livestock, rattle windows, and disturb people. In 1973, strongly influenced by public opinion, the Federal Aviation Administration banned overland commercial supersonic flight in the US; similar restrictions were also enacted in other countries.

In the coming months, Lockheed Martin Aeronautics will test-fly a plane it designed and built for NASA under a \$247 million contract. The X-59 is intended to create a quiet “sonic thump” at

supersonic speeds. Starting in 2026, NASA will ask the public to weigh in to see whether the noise is sufficiently muted to gain acceptance for overland supersonic flights.

Greg Ulmer is the executive vice president of Lockheed Martin Aeronautics. At the 12 January unveiling of the X-59, he called it “an experimental technology demonstrator that has the potential to completely revolutionize aviation.” If the X-59 is deemed quiet enough, and if the law banning commercial supersonic flight over land is overturned, then companies could pick up where Lockheed Martin and NASA have left off and commercialize supersonic flight.

## A computational feat

Every change in a plane’s shape and every feature on its surface, from the tiny screws to the engines, creates a shock wave at supersonic speeds. The shock waves are nonlinear and tend to coalesce at the front and back of the plane; each generates a sudden change in pressure, hence the double boom, explains Jay Brandon,

NASA’s chief engineer on the project.

The concept of shaping a plane to minimize the amplitude of the generated shock waves and to prevent them from aggregating has been around for decades. The aim “is to spread out the shocks. We want to smooth the pressure changes,” says Brandon. “That way we prevent a loud sonic boom that sounds like an explosion.”

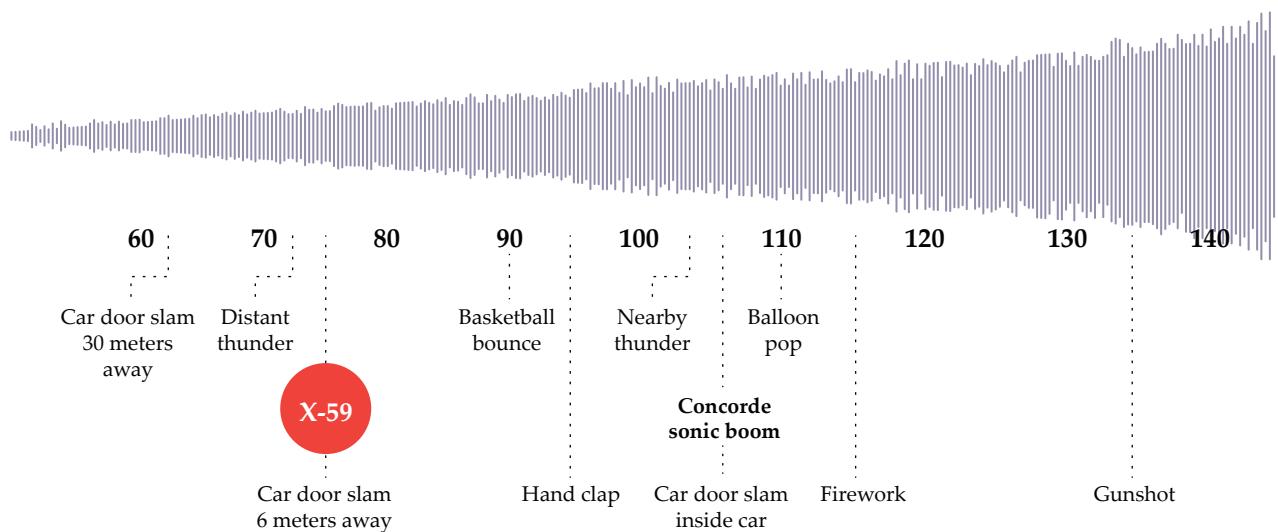
Advances in supercomputers have “enabled us to model the equations for airplane shape and the surrounding fluid dynamics,” Brandon says. Modeling the flow effects that the airplane shape produces wasn’t possible with earlier generations of computers, he adds.

Simulations can be used to help design the shaping characteristics needed for a low-boom airplane operating in realistic flight conditions, says Brandon. The traditional approach of building physical models and testing them in wind tunnels would miss some aspects of shock wave propagation, he notes, and it would have been much slower and costlier. A single iteration could take years, compared to



LOCKHEED MARTIN AERONAUTICS

**DESIGNED TO FLY SUPERSONICALLY YET QUIETLY**, NASA’s X-59 was unveiled by Lockheed Martin Aeronautics in Palmdale, California, earlier this year. The plane is being developed as a first step to future overland supersonic commercial travel.



**COMPARED WITH OTHER SHORT-DURATION SOUNDS**, the boom from NASA's new supersonic plane, the X-59, is perceived to be about as loud as a car door slamming from a distance of 6 meters. The perceived level in decibels increases from left to right. (Adapted from a diagram provided by NASA.)

weeks or months with simulations. With the X-59, wind tunnels were used to validate computational predictions.

The X-59 has a sleek, 30-meter-long body. It is about 4.2 meters tall, and its wingspan is about 9 meters. Its single engine is located atop its body to divert downward-propagating shock waves produced by the engine inlet. Its elongated nose spreads out the shock waves to reduce the noise heard on the ground. The plane has no front window, says Brandon, because the shape and angle of a window needed for good visibility are inconsistent with the streamlined contours that minimize shock waves. Instead, the pilot will use high-definition camera images that line up seamlessly with the views from side windows.

Flying without a front window has been vetted in tests with subsonic aircraft. The engine, hydraulics system, and other aspects of the X-59 have also been adapted—and in some cases, refurbished—from existing craft. For example, says Brandon, the landing gear is from an F-16 fighter jet, the canopy is from the back seat of a T-38 aircraft, and the engine is a slightly modified version of the one used in the F/A-18E fighter jet.

Lockheed Martin designed the plane with a target perceived level in decibels (PLdB) of 75. For comparison, the Concorde, which transported passengers

across the Atlantic Ocean for three decades at Mach 2, or twice the speed of sound, produced sonic booms of about 108 PLdB. It was discontinued in 2003 after a crash in 2000 and the terrorist attacks of 11 September 2001 dampened demand.

NASA set an upper limit of 75 PLdB for the X-59 based on laboratory experiments. "Volunteers inside simulators indicated low levels of irritation at that level," says Jonathan Rathsam, an acoustics specialist and the technical co-lead for NASA's community-response phase for the X-59. "It's also what is currently achievable with an aircraft of this size." The energy in the thumps peaks around 10 hertz, he says. Volunteers likened the sound to that of a car door slamming 6 meters away.

The aircraft will fly at Mach 1.4; at its design altitude of about 16 000 meters, that's about 1488 km/h.

### Testing public acceptance

For the public-perception surveys, Rathsam says, flights will regularly traverse large swaths of land for a month at a time, and people below the flight path will be asked for their opinions via online surveys. "We have our models, predictions, and wind-tunnel data," he says. "But we can't know for sure what the response from communities will be. The effort requires real response data. There is no way to simulate that."

The perception tests will run for about three years. NASA will also conduct acoustic measurements of the absolute noise from the X-59.

After that, it will be up to industry to take on the jobs of requesting that the overland speed limit be removed or amended and of developing commercial passenger carriers. Lockheed Martin and NASA officials say they do not foresee military applications.

The pilot is the lone person aboard the X-59. But, says Brandon, a key design requirement was that results from the craft be scalable. A possible passenger carrier would be, per Lockheed Martin's calculations, about twice as long as the X-59 and able to seat up to 44 passengers.

But the boom and legal overland speed limit are not the only hurdles to commercial supersonic travel. Emissions, fuel consumption, and the noise at takeoff and landing must also pass muster. Originally the X-59 was supposed to be designed to use sustainable fuel, says Brandon, but NASA dropped that requirement. "We focused on the thump."

"If you look at the history of air travel, it was for the elite at the beginning," notes Brandon. "But as the technology matured, it became more accessible. I would expect that supersonic flight will eventually be for everyone."

**Toni Feder** 



JASON KEISLING

**Michael Marder** is a professor of physics at the University of Texas at Austin.

**Frances Houle** is a senior scientist at Lawrence Berkeley National Laboratory in California. **Kate Kirby** is CEO emerita of the American Physical Society.



# The ethics perspective of physics department chairs

Michael P. Marder, Frances A. Houle, and Kate P. Kirby

**Although a new American Physical Society ethics survey shares some conclusions with a previous one, disparities between the two highlight the need for improved procedures and open communication channels in physics departments.**

**H**ow is ethics knowledge shared in the physics community, and what is the state of ethical practices in physics departments? The Ethics Committee of the American Physical Society (APS) wanted those questions to be answered by key members of physics departments: students, postdocs, and faculty.

According to the Effective Practices for Physics Programs guide, developed by APS and the American Association of Physics Teachers, “Ethics is a cornerstone of effective scientific practice. . . . Ensuring that all physicists behave ethically maintains the integrity of physics as a discipline and supports public trust in physics and in science as a whole.”<sup>1</sup> Physics departments at colleges and universities across the US and around the world play a vital role in the education of future physics professionals. Ethics education—for instance, offered formally through a course or webinar, informally through examples set by mentors and advisers, or discussions in a research group—is an essential part of a physics education.

The APS Ethics Committee, which the three of us were part of, distributed a survey in 2020 to graduate students and early-career APS members who had obtained their PhD within the past five years. (See our article in *PHYSICS TODAY*, January 2023, page 28.) The survey was a follow-up to a similar one in 2003, which looked specifically at how ethics are taught and at how aware so-called junior members, those who earned their PhD within three years of the survey, were of ethical practices in physics. (See the article by two of us, Kirby and Houle, in *PHYSICS TODAY*, November 2004, page 42.) The responses to the 2020 survey, hereafter called the early-career survey, show that unethical research practices and harassment continue to be a significant problem in the physics community but go largely unreported for various reasons.

In parallel with the early-career survey, the APS Ethics Committee also polled the chairs of physics departments. The ethics questions were part of the biennial Academic Workforce Survey, which was carried out in March 2020 by the Statistical Research Center of the American Institute of Physics (publisher of *PHYSICS TODAY*). Responses were received from 622 of 766 degree-granting physics departments (81%). The intent of the survey was to understand the perspective of chairs regarding ethics and ethics education in their departments. In this article we first summarize the principal results from the department chairs survey and then compare the results with those from the early-career survey. The different perspectives of department chairs and early-career APS members reveal concerns and opportunities for physics departments to better support a culture of ethics.

## The findings

Our 10 most striking findings from the department chair survey are listed in the box on page 24. In many cases, the responses from PhD-granting and bachelors-only programs were not significantly different. Departments granting bachelors degrees only, however, are more likely to report that all faculty must take ethics training, less likely to offer a semester-long course on ethics, and more likely to report zero ethics violations. A number of department chairs from bachelors-only programs pointed out that because the survey questions seemed to assume that graduate students were in their

## Ethics in physics departments

These ethics findings, listed from least common to most common, are from a survey, funded by the American Physical Society (APS) and conducted by the American Institute of Physics (publisher of PHYSICS TODAY), of physics department chairs.

10. One chair in 10 (10%) does not know whether full-time faculty members are aware of the procedures to report ethics violations.
9. At least one chair in five (about 20%) does not know whether part-time faculty, postdocs, and graduate and undergraduate students are familiar with the procedures to report ethics violations.
8. About one-third (35%) of the chairs do not believe that the institutional processes are adequate to enforce ethical behavior and ensure that justice is served.
7. Less than half (40%) the chairs believe that their graduate students have a good understanding of what constitutes ethical behavior in science.
6. Almost half the chairs (45%) report that their department does not offer ethics training.
5. More than half (59%) the chairs believe that the procedures are clear for following up on the progress and resolution of any reported ethics violation.
4. About two-thirds of the chairs (65%) believe that the procedures for following up on progress and resolution of any reported ethics violation are readily available.
3. Two-thirds of the chairs (66%) report having no ethics violations in the past five years.
2. Three-fourths of the chairs (74%) believe that APS has a role in providing ethics training.
1. A large majority of chairs (85%) believe that most of their faculty members have a good understanding of what constitutes ethical behavior in science.

program, they were difficult to answer, but we do not believe that that significantly affected the results.

Although the particular questions and the response rates from the early-career and department chair surveys were quite different, several responses seem consistent. We focus, however, on the discordant messages from the two sets of results.

Figure 1 contrasts how department chairs and early-career scientists responded to the question of ethics training. Nearly half the chairs reported that their departments do not provide ethics training. For those who said that training is offered, most singled out webinars or online modules as the main type. By contrast, only 4% of the early-career APS members said that they did not have ethics training. The difference comes about because 40% of the early-career respondents said that they received their ethics training through their research group. That is potentially problematic because many ethical dilemmas, such as pressure to falsify data, come from research supervisors.

In the early-career survey, graduate students and other early-career participants were asked to recommend the kinds of trainings that they thought would be useful. Among the most suggested types were courses, workshops, seminars, and discussions on such topics as how to treat people, organize a research record,

and write a paper. Opinions on the value of Web-based trainings were mixed: Some said that they were useful, whereas others pointed to the value of in-person discussions to help illustrate the gray areas in ethics decisions. Several survey participants emphasized the value of having trainings for department members at all levels, including faculty. Here is a sampling of responses from early-career APS members:

*"My institution has computer-based ethics-training courses we have [to] take once a year, so that's an option. . . . But it's also a pain and nobody really takes it seriously."*

*"In my experience, young physicists don't want more meetings, but they love critically thinking to answer difficult questions. The most effective method I've encountered in a more formal setting is open-forum discussions of no more than six people in a group, being given appropriately complex ethical puzzles to discuss freely."*

*"At some level, I believe mandatory training would be the most effective. From personal experiences, many people view ethics as a known quantity without the need for review or training. However, there are many details to ethics that this viewpoint doesn't account for."*

*"Faculty, especially older generations, need ethics training—perhaps on a regular basis. This needs to be required on an institutional level. Either they were never trained in ethics, or they were but get caught up in politics or don't think ethics are important or don't think they are doing anything wrong. Students and the scientific enterprise suffer as a result. Students have plenty of ethics training, but we don't have the power to ensure that everything is carried out ethically."*

*"Not sure: formalized classes and trainings are often viewed as a bother/nuisance, especially if the examples given are obvious. Presenting ethical dilemmas that are commonplace and relatable (and gray, rather than obviously unallowable conduct) may lead to more robust discussion about the range of appropriate responses."*

Training practices across departments differ. The departments granting only bachelors degrees are more likely to have mandated ethics training for all faculty, whereas departments granting PhDs are more likely to offer a semester-long ethics course. According to written comments by the department chairs, training can mean various things depending on the institution.

*"We do have some visibility regarding harassment policies on-campus, which is more specific. We do have Diversity, Equity, and Inclusion training and initiatives for all employees, particularly related to campus climate studies. We do not have as many visible activities regarding ethics, [which] I take to be more general."*

*"We take a hard-line approach on cheating, plagiarism, etc. and we try to model ethical behavior for students. We have [an] ethics course in [the] general curriculum. Our majors also complete specific ethics-related content (class discussions and HW) in our Advanced Lab course."*

*"The training for students is understood and needed as part of the graduate school in particular. It is spottier for the undergraduates and the faculty and staff. The training should be formalized and improved."*

## Limited reporting

An unsettling picture of the reporting of ethics violations emerged when we compared the information from the department chair survey with that from the early-career survey. In response to the question "Have you ever observed or had personal knowledge of ethical violations during your time as a graduate student or as a postdoc?" some 288 (38%) early-career respondents who witnessed an ethics violation knew where to report it; the remaining 469 (62%) did not. They wrote 517 comments and described 527 cases of ethics violations. Respondents said that they themselves had provided institutional reports on 108 of the cases and that a total of 131 reports were filed, whether by themselves or someone else. Out of the 527 cases of ethics violations, 60 were resolved in a way that the respondent thought was satisfactory. Thus, according to the responses, roughly only 20% of ethics violations had institutional reports, and of those, only a bit more than half were resolved well in young physicists' eyes.

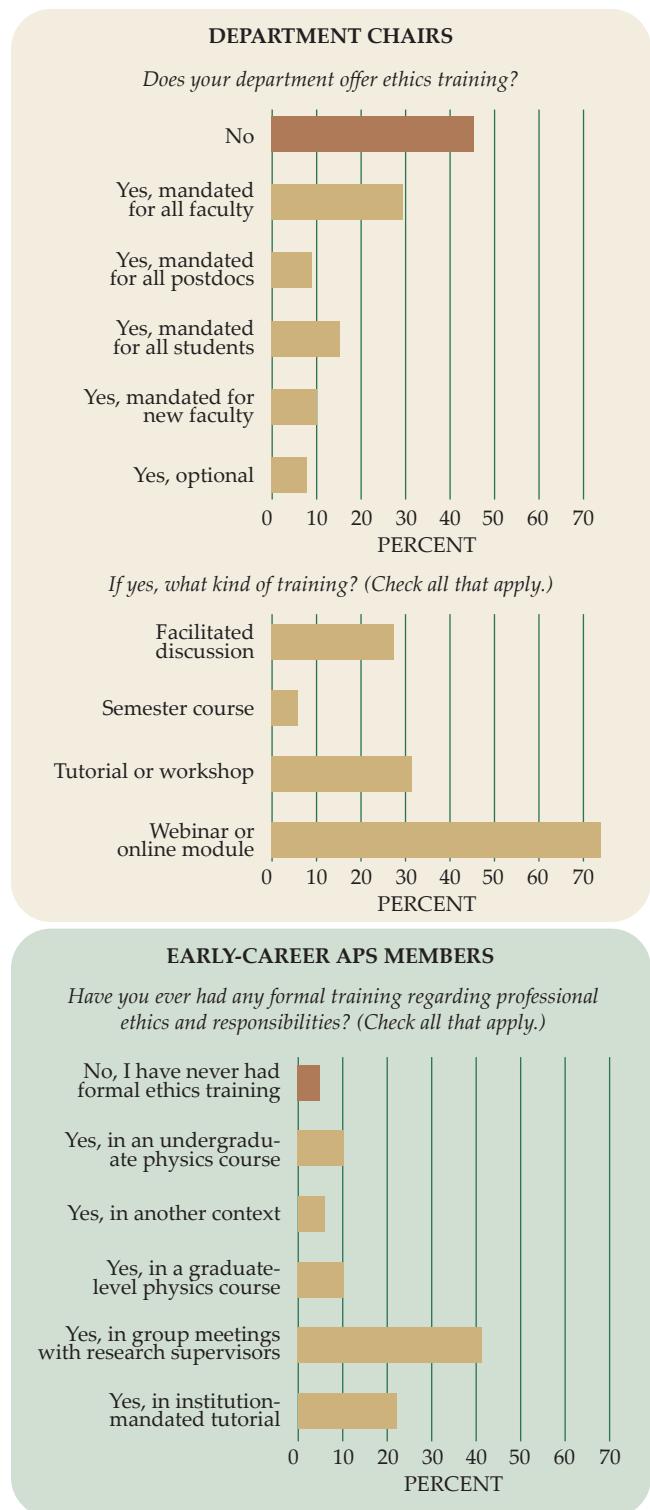
Figure 2 shows ethics-violations data from the department chair survey. The 622 chairs who responded—yielding a response rate of 81%—reported more than 600 reported violations in the past five years, although most chairs said that they knew of none. In comparison, only 25% of postdoc and graduate-student APS members responded to the society's early-career survey: Early-career APS members, who had obtained their PhD within the past five years, said that 131 violations were reported to authorities.

We are not sure how to reconcile the disparate findings, but one plausible scenario is that about 500 ethics violations may have been reported to authorities by early-career APS members if the response rate of 25% was extrapolated to 100%. That number of violations is not far below the 600 that chairs said they knew about. Department chairs may receive violation reports from others beyond graduate students and postdocs, so having early-career members report 500 estimated violations could be reasonable.

If the interpretation is correct, the majority of chairs lack effective communication channels for people to feel safe reporting ethical dilemmas they face or have witnessed. The majority of cases go unreported. The 66% of chairs in figure 2 who said that they dealt with no ethics violations in the past five years should be concerned by the possibility that cases occurred but were not reported. Here is a characteristic description of what students face:

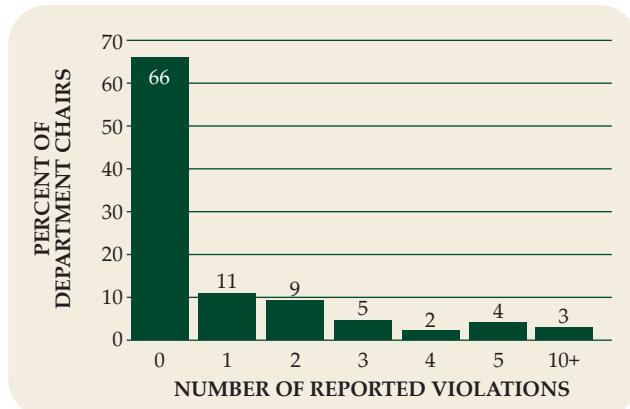
*"I did not report because I did not know the avenues to report and the person has significant influence in my career."*

The perspectives from the chairs and early-career scientists on ethics education and the experience of ethics violations in physics departments reveal important disconnects. Many early-career respondents have specific views on what types of ethics-related education would be useful to them beyond what they obtain through research-group activities. The need for ethics education has not risen to the same level of urgency among department chairs. They may have an overly favorable view regarding ethical practices in their departments, which is understandable if students and postdocs do not report 80% of the infractions that they experience, observe, or have been told



**FIGURE 1. PHYSICS DEPARTMENT CHAIRS** describe their ethics training compared with the training that early-career members of the American Physical Society say is offered. (Courtesy of APS.)

about. The lack of reporting is because of a fear of retaliation—for example, not getting a good letter of recommendation, not receiving a PhD in a timely fashion, or being given less recognition or help in research—and the concern that justice would



**FIGURE 2. FEW REPORTED VIOLATIONS.** When department chairs were asked, “How many reports of ethics violations have you dealt with over the past five years?” 9 out of 10 (91%) responded that they dealt with three or fewer. (Courtesy of the American Physical Society.)

not be served by reporting. According to one respondent:

*“I did [report it] to my department first. I was warned by a female no less that even if I succeed in getting justice it never works out for the victim in the end. I was told I was better off graduating in good terms with everyone. I let my advisor know about it and while he ‘said’ he was supportive and gave me advice on who to talk to he never did anything to help me out nor ever asked about it ever again.”*

We did not survey physics undergraduates, and filling that gap would produce a more complete perspective of physics departments. Five years ago, however, undergraduate women attending the APS Conferences for Undergraduate Women in Physics were surveyed regarding whether they had been sexually harassed in the context of their physics education. The results showed that a shocking 75% of them experienced sexual harassment, most of which was never formally reported.<sup>2</sup> The Federal Policy on Research Misconduct, put out by the Office of Science and Technology Policy in 2000, does not include sexual harassment as one of its unethical practices, which it defines as fabrication, falsification, and plagiarism. The American Geophysical Union, however, has elevated sexual harassment to the same level of misconduct as the federal policy,<sup>3</sup> and APS has included extensive material on harassment and bias in its 2019 ethics guidelines.<sup>4</sup> Mistreatment of people is now considered by almost all scientific institutions, universities, and national and industrial labs to be a serious ethical breach.

Many scientists argue that the lack of accountability in departments is problematic because it allows ethics infractions to be ignored, perpetrators to continue their harassment, and toxic environments to persist.<sup>5</sup> In the survey, department chairs say that they refer reports of harassment to higher administration officials or Title IX offices, which places the investigations outside the department. That approach, to a certain extent, may be required by the college or university, but it can absolve a department chair from taking responsibility for holding anyone accountable for infractions. It may appear to those lower down in the academic hierarchy as a way of passing the buck.

Elevating harassment cases to other offices also discourages people from reporting ethics violations: One early-career APS

member warned that “nothing will happen to address them.” In many institutions, the role of a department chair is temporary—often three to six years—and a chair might feel quite hesitant to bring one of their colleagues to account because of fears of retaliation. Although faculty members and department chairs are mandated to report sexual harassment, they are not required to inform authorities about research misconduct issues related to fabrication, falsification, and plagiarism.

## How to improve ethical behavior

Most department chairs were quite positive that APS could contribute considerably to ethics education. They were interested in APS webinars, case studies, and other materials that could start educational conversations about ethics in physics. Chairs may be eager to engage their department on ethics topics, but they feel that they lack resources and know-how.

Webinars and online ethics-training modules, however, may not be effective. Survey results showed that 55% of responding NSF graduate research fellows in several science and engineering disciplines felt that “mandatory ethics training left them unprepared to deal with ethical issues.”<sup>6</sup> Because ethics violations almost always involve humans acting badly and the circumstances are not always clearly right and wrong, how to apply ethics training can be confusing. Designing effective training, such as discussion-based seminars and examination of real-life cases that can be widely shared, will help build the capacity across physics departments to prepare students more effectively.

As outlined in the ethics section of APS’s Effective Practices for Physics Programs guide, establishing a culture of ethical behavior with respect to teaching, learning, and research in a department is imperative.<sup>1</sup> The chapter includes detailed suggestions for getting buy-in from and raising the profile of ethics in the department. The early-career respondents emphasized the importance of good role models. For example:

*“I think training facilitated and taught by senior physicists for junior physicists would be most effective. This would both teach valuable information and model/show younger physicists that their senior colleagues value and are receptive to ethical issues.”*

In a hierarchical department, students may not feel comfortable talking to the chair about an infraction. It is often thought to be best practice to appoint a neutral party: someone who is well regarded, who may be from outside the department, and who can maintain confidentiality so that difficult issues can be explored and discussed. Some questions that may arise include the following: Did the person really commit a breach of ethics? Were they aware of the rules? Was the person exhibiting disrespectful behavior? Which options are available for dealing with the situation? Providing multiple lines of communication would also be valuable to accommodate diverse personalities and department structures.

Many institutions appoint an ombudsperson to serve as a neutral third party. In some cases the position provides a positive institutional contribution when problems arise. On the other hand, some worry that an ombudsperson has little power and therefore deflects problems. The respondents to our early-career survey provided some information on the two views. In the 517 comments described above on institutional responses to ethical failings, only two referenced an ombudsperson. In each of those cases, the respondent said that they were dissatisfied with the

institutional response. Because of a lack of mention, we cautiously conclude, therefore, that the ombudsperson is often not effective in addressing ethics violations.

Is there any common thread binding together the 60 ethical problems that early-career APS members thought were resolved well? We have only 15 comments that provide more detail beyond that the matter was reported and resolved. In 12 of them, a group leader or PhD adviser led the resolution; in three, it was journal editors. A critical element for improving institutional response, therefore, may be the establishment of a trust network between and among students, faculty, postdocs, research advisers, and the department chair. Without trust, ethical concerns will not be reported. Developing trust demands open lines of communication and an institutional willingness to address problems.

Taken together, the results of the department chair and early-career surveys show an evolution of ethics awareness over the past two decades. Ethics education has improved: 95% of early-career respondents say they had some kind of ethics training—mostly in research groups or through institutionally mandated, and usually Web-based, tutorials. Many of the early-career comments, however, show that Web-based training is not valuable and does not equip the learners with the necessary tools to deal with real-life ethical issues. Physics departments should give more attention to ensuring that faculty, staff, and students have a clear and complete understanding of ethical principles, should consider other methods of teaching about ethics issues beyond Web-based modules, and should provide safe ways for people to raise concerns. Chairs listed positive

actions that APS could take to help them build an ethical department culture. Most importantly, it is clear that dialog and open communication are essential to enabling everyone in the physics profession to continue to improve ethical behavior.

*The authors thank the many people who have contributed to this work, especially the department chairs who responded in such great numbers to the most recent survey. Susan White and Julius Dollison of the American Institute of Physics' Statistical Research Center administered the department chairs survey and analyzed the data; Jeanette Russo, APS corporate secretary, worked extensively on the surveys; and the APS Ethics Committee members contributed their ideas and suggestions. Michael Marder acknowledges many years of research support from the NSF Condensed Matter and Theory program for which work on ethics in physics has been part of its broader-impacts contribution.*

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**Mohammed Kaplan** is an assistant professor of microbiology at the University of Chicago.



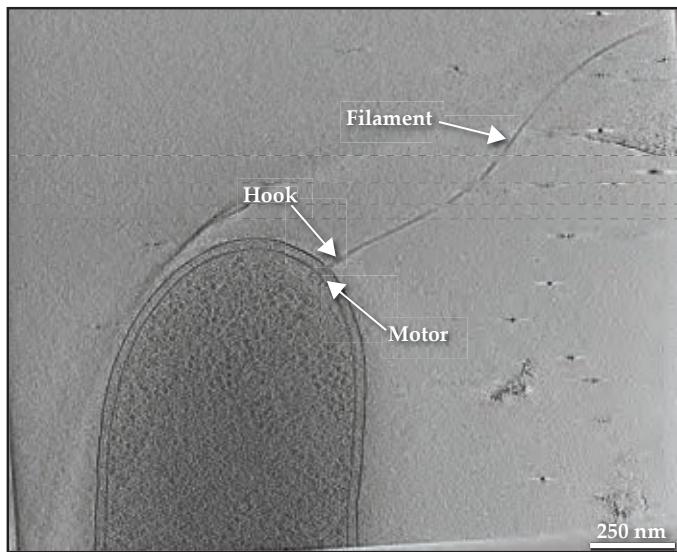
# The connection between Darwin's finches and bacterial flagellar motors

**Mohammed Kaplan**

**The evolution of specialized biological tools used by organisms tells a story about the environments that shaped them.**

Watching bacteria dance in a droplet of water under a microscope is an awe-inspiring experience that evokes emotions of wonder, like those one might feel while observing stars in the sky. Bacteria's motility is the result of billions of years of evolution, and in many species, it is driven by a glorious macromolecular structure known as the flagellum. That biological masterpiece consists of multiple distinct parts, as seen in figure 1: a long proteinaceous filament protruding outside a bacterium like a tail; a motor embedded in the cell-envelope membrane(s), located at the filament's base; and a flexible universal joint in between, known as the hook. The motor generates a torque that spins the filament to move the cell in a propeller-like fashion.

# BACTERIAL FLAGELLAR MOTORS



**FIGURE 1. A SWIMMING BACTERIUM** uses a flagellum to power its motion. A slice through a cryo-electron tomogram of a *Shewanella oneidensis* cell illustrates the filament, motor, and hook that make up the appendage.

The structure, function, and assembly of the motor have long captured the imagination of both academic scholars and science popularizers (see the article by Howard Berg, PHYSICS TODAY, January 2000, page 24). To assemble its flagellum, a bacterium must regulate and synchronize the expression, export, and placement of dozens of proteins and thousands of protein subunits. Interestingly, flagellar motors exhibit a huge structural diversity among bacterial species, suggesting an evolution of their form over time.

In 1835 Charles Darwin arrived at the Galápagos Islands during the course of his famous voyage aboard the *Beagle*. There he studied many biological species, including what became known as Darwin's finches, the birds that inhabit different areas of the islands. Those birds share a common ancestor—the dull-colored grassquit—that lives on mainland South America, but they have evolved a remarkable variety of beak types to suit their characteristic, area-specific food chains. For example, birds with blunt beaks usually feed on seeds, while those with long and sharp beaks tend to hunt for and grab insects. They represent iconic instances of evolution and adaptation to the environment. In a certain way, the same is true for bacterial flagellar motors.

All bacterial flagellar motors discovered to date have similar shared core structures. Several bacteria species, however, have developed embellishments that optimize the motor to suit a specific environmental niche. For instance, species that inhabit more viscous environments have enhanced motors with extra components to generate higher torque.

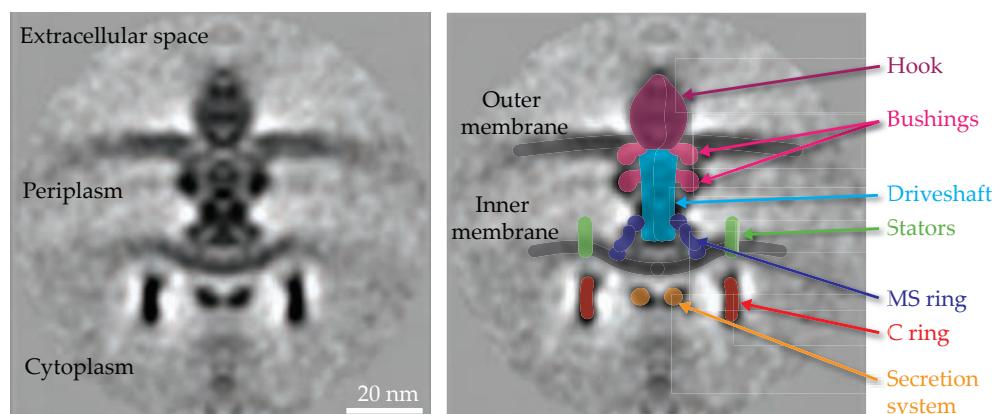
The diversity of flagellar motors is a prime example of the ongoing evolution of macromolecular biological machines, comparable to the diverse beaks of Darwin's finches. The flagellar motor characteristic of a given species can, in fact, be viewed as a "molecular fossil," and every time the architecture of a different motor type is revealed, a new tile clicks into the jigsaw puzzle of how those amazing nanomachines have evolved over time.

For the sake of simplicity, the scope of this article is limited to bacteria with a cell envelope containing inner and outer membranes. All slices of cryo-electron tomograms or subtomogram averages of flagellar motors depicted here represent 2D cross sections through 3D reconstructions of the protein complexes. Therefore, a cross section through a ring appears as two dots (for example, the bushings in figure 2), and a cross section of a short cylinder through its axis appears as two parallel lines (for example, the cytoplasmic C ring in figure 2).

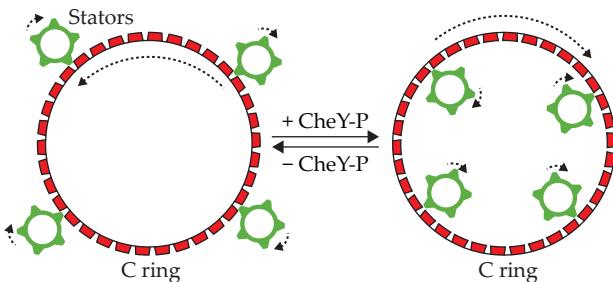
## Anatomy of a flagellar motor

In his book *The God Delusion*, Richard Dawkins wrote of the flagellar motor, "It derives the only known example, outside human technology, of a freely rotating axle." The components of a flagellar motor, like the *Escherichia coli* motor seen in figure 2, are much like the mechanical and electrical motors that people encounter on a daily basis. It is composed of a rotor that spins, a stator that surrounds and drives the spinning of the rotor, a driveshaft (axle) to transmit the torque generated by the rotor–stator assembly, and bushings that surround the driveshaft to reduce vibration and friction during torque transmission.

The rotor comprises a series of rings, including the cytoplasmic ring, known as the C ring, and the inner-membrane embedded ring, or the MS ring. A dedicated secretion system delivers proteins—used to build the driveshaft, hook, and filament—across the inner membrane to the periplasmic space (the space between the inner and outer membranes, shown in figure 2) and outside the cell. Extending from the rotor, and through the periplasmic space is the driveshaft, which transmits torque through the flexible hook and ultimately to the extracellular filament that moves the bacterium. Two other rings that surround the driveshaft act as bushings. The driveshaft extends to the outer membrane, with the hook and filament mounted on top of it,



**FIGURE 2. THE *ESCHERICHIA COLI* FLAGELLAR MOTOR** is made of many components that play similar roles to the standard parts of a mechanical motor. A central slice through a subtomogram average of the flagellar motor (left) is overlaid with labeled component parts (right).



**FIGURE 3. ROTATIONAL SWITCHING** of the flagellar motor is accomplished by changes to the C ring's shape and position, which are controlled by a cytoplasmic protein (CheY-P). Stators always spin clockwise, so when they engage the outer surface of the C ring (left), the motor spins counterclockwise. When stators engage the inner surface of the C ring (right), the motor spins clockwise.

outside the cell. The exception is in a group of bacteria known as spirochaetes, in which the hook and filament are retained in the periplasm and form what is known as an endoflagellum.

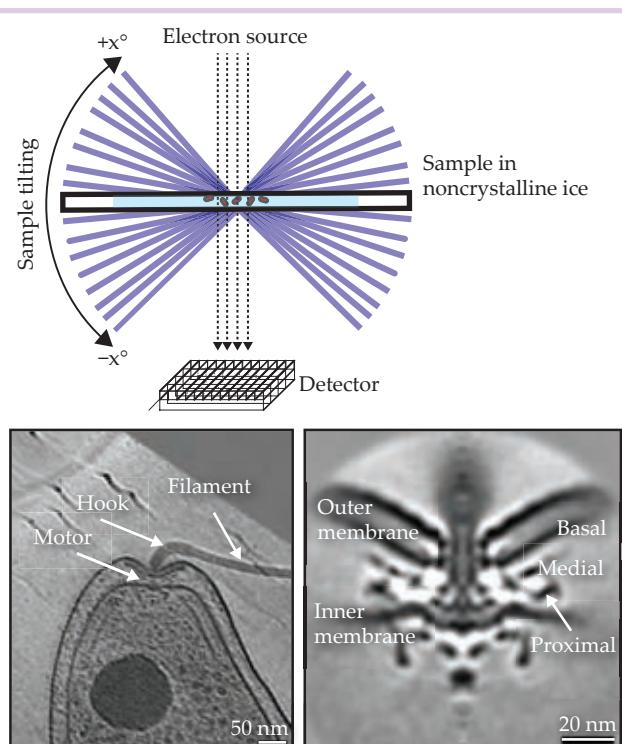
Stators, which are ion channels embedded in the inner membrane and surround the rotor, generate torque by using ion motive force produced by electrical and chemical potential differences across the cell membrane. Recent work has revealed the mechanism of stator–rotor interaction that generates the torque and drives both cell motility and a rotational switching mechanism.<sup>1–3</sup> Stators appear to operate like smaller rotors themselves, spinning as they pump ions across the inner membrane and interacting with the upper part of the C ring to drive

its rotation and thereby generate torque, as shown in figure 3.

While stators always spin clockwise, the motor can alternate between spinning clockwise (CW) and counterclockwise (CCW) by using a clever trick. When the outer surface of the C ring is touching the CW-spinning stators, the C ring spins in the direction counter to that of the stators, and the motor rotates CCW, as shown in the left panel of figure 3. Binding of another cytoplasmic protein, CheY-P, to the C ring, however, changes its shape and diameter, thus making it wider.<sup>1,4</sup> So much so, in fact, that the CW-spinning stators end up touching the inner surface of the C ring instead of its outside rim. The result is that the C ring spins CW in concordance with the stators, as shown in the right panel of figure 3.

## Macromolecular structural diversity

The structure of the motor outlined in figure 2 represents the conserved-core architecture typical of all bacteria with outer and inner membranes. Widely studied species of *E. coli* and *Salmonella enterica* are known to possess bare conserved-core motors. With the advent of recent imaging techniques, such as cryo-electron tomography (cryo-ET, see the box on this page), that enable direct visualization of macromolecular complexes in intact frozen-hydrated cells, an astonishing structural diversity of flagellar motors evolved by different species has become observable.<sup>5</sup> Whereas all the motors known to date possess the C ring, the MS ring, the driveshaft, and the bushings, many



**THE CRYO-ET DATA COLLECTION METHOD** used to produce images of bacteria is illustrated in the upper panel. A slice through a cryo-electron tomogram of a *Campylobacter jejuni* cell depicts the different parts of its flagellum in the lower left panel. A central slice through the subtomogram average of a *C. jejuni* flagellar motor,<sup>6</sup> in the lower right panel, highlights its specific periplasmic disks—basal, medial, and proximal.

## Seeing inside bacteria with cryo-ET

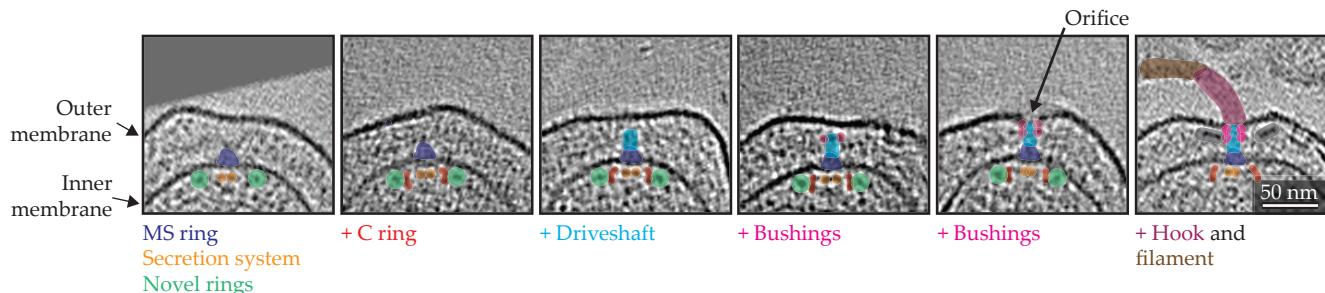
In cryo-electron tomography, or cryo-ET, cells are plunge-frozen on an electron microscope grid using an efficient coolant, which prevents the formation of ice crystals and instead promotes the development of vitreous (noncrystalline) ice. Subsequently, a transmission electron microscope takes a series of images at different tilt angles as the sample is rotated. Typically, images are taken every 1° to 3°. The 2D images are then computationally combined to build a 3D reconstruction of the sample at a resolution of a few nanometers, which allows for the visualization of macromolecular complexes inside the individual, intact hydrated-frozen cells.

The overall resolution can be improved by performing a subtomogram averaging procedure, wherein fragments of the tomogram containing a complex of interest—for example, a bacterial flagellar motor—are computationally identified, cropped, aligned, and averaged together.

The power of cryo-ET lies in its ability to produce images of macromolecular complexes in their native cellular milieu, without the need to purify or perturb them, and at a macromolecular resolution. In other words, its strength lies in avoiding the specific concerns that Johann Wolfgang von Goethe expressed in *Faust*:

When scholars study a thing, they strive  
To kill it first, if its alive;  
Then they have the parts and they've lost the whole,  
For the link that's missing was the living soul.

# BACTERIAL FLAGELLAR MOTORS



**FIGURE 4. ASSEMBLY STAGES** of a flagellar motor in a *Hylemonella gracilis* cell. The highlighting in the tomographic slices shows the addition of motor components.<sup>12</sup> Novel cytoplasmic rings (green circles) are present for most of the assembly but are absent from the fully assembled flagellar motor shown in the right-most panel. Assembly of the bushings leads to the formation of an orifice in the outer membrane where the hook and filament are attached.

species have a modified conserved core with, for example, some extra motor components.

Just like every bird type of Darwin's finches evolved a beak that suits the food sources available in its milieu, every bacterial species evolved its characteristic macromolecular motor structure to suit the environmental niche it inhabited.<sup>6,7</sup> For instance, the motor of the pathogen *Campylobacter jejuni*, shown in the box on page 31, features various additional periplasmic disks that help position the stators at wider radii around the driveshaft to produce greater torque than the conserved-core motor. That extra torque is paramount in viscous environments, such as the mucous layer of the human stomach.<sup>6</sup>

A crucial point about evolution is that it is not always progressive. Although it sometimes leads to increased complexity, traits can also be lost during the evolutionary process if that loss proves beneficial for the species.<sup>8</sup> Therefore, just because *E. coli* has the bare conserved-core motor does not necessarily

mean that its motor is "older" or "ancestral" to others. In fact, recent work has shown that the *E. coli* motor is not native to that particular species but, rather, has been acquired from other bacteria through gene-transfer mechanisms.<sup>9</sup> That turns out to be advantageous because the generic motor easily adjusts to suit the various environments that *E. coli* commonly encounters in its niche, such as in the gut.

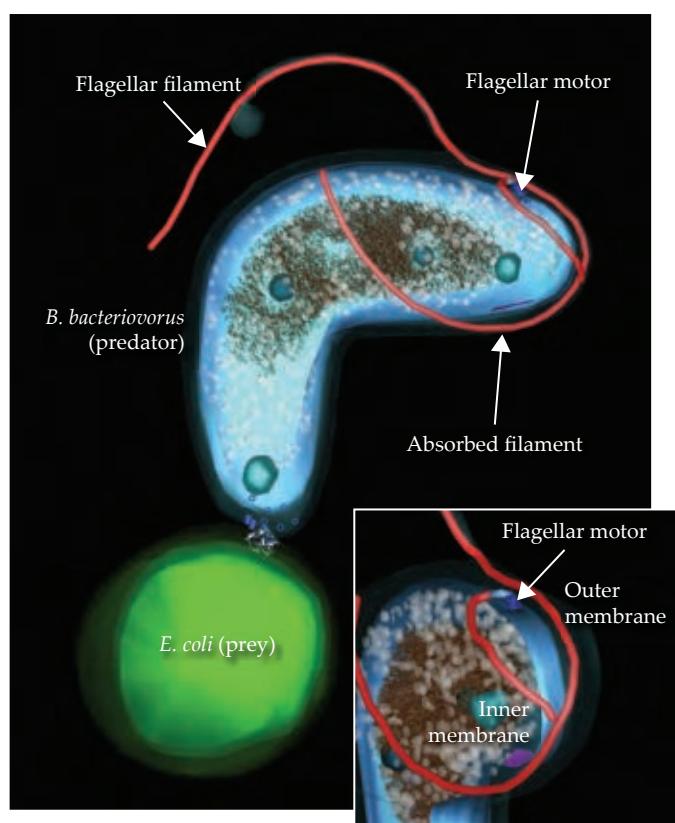
Structural diversity is not limited to the motor alone. For example, spirochaetes evolved endoflagella—or periplasmic flagella—where the hook and the filament remain in the periplasm. That configuration, with the filament wrapping around the cell beneath the outer membrane, results in the bacteria moving by rolling or undulating in highly viscous, gel-like environments. Other species, including many pathogens, have what is called "sheathed flagella," with the outer membrane extending to surround the hook and the filament. The way by which the sheath forms, and its exact function, remains enigmatic, but it could be a way for the bacterium to circumvent the host immune system by sequestering the flagellar filament protein inside the sheath to prevent a reaction to that protein by the host.<sup>10</sup>

## Building a flagellar motor

The process by which a bacterial cell assembles a flagellar motor has long fascinated scientists. How do individual proteins of all kinds assemble into such an intricate nanomachine? Since the flagellar motor consumes a significant amount of precious cell energy, its assembly is tightly regulated. Its biogenesis is, in a sense, inside out: Components associated with the interior of the cell tend to assemble first, and the process propagates upward through the periplasmic space and on to the outer membrane,<sup>11</sup> as shown in figure 4.

At the beginning of the process, the inner-membrane components assemble, and, subsequently, the driveshaft proteins click into place. On completion of the driveshaft biogenesis, the bushings are built around it. The formation of the bushings reshapes the outer membrane to create an orifice, thereby allowing the assembly of the extracellular hook and filament.

The above process, however, is not merely an accretion of



**FIGURE 5. A PREDATOR BACTERIA CELL**, *Bdellovibrio bacteriovorus*, is in the process of capturing an *Escherichia coli* minicell. When catching a prey bacterium, *B. bacteriovorus* retracts its extracellular hook and filament into its own periplasmic space, shifting the motor to the side to make room for the retraction process.

the component proteins. It appears to be dynamic, with various chaperones and enzymes involved. Chaperones are proteins that help with folding and translocating other proteins to their cellular locale. Recent intracellular cryo-ET imaging of the motor biogenesis process has revealed transient cytoplasmic rings (shown as green circles in figure 4) that assist the assembly of the motor at certain intermediate stages. Those novel rings surround the C ring at early assembly stages, but they are, notably, absent in the fully assembled motor. The exact function of the transient rings remains obscure, but one hypothesis is that during the assembly process they help stabilize the stator units surrounding the MS ring.<sup>12</sup>

The biogenesis processes of various embellishments to the conserved-core motor are not yet fully understood. In one interesting case though, an extra periplasmic disk in the bacterial species *Wolinella succinogenes* was observed assembling in a manner akin to an Archimedean spiral, with a protein polymerizing to build a spiral around the bushings.<sup>13</sup> Future observations may reveal equally novel construction mechanisms among those embellishments.

## Disassembly processes

Whereas the process of flagellar assembly has been under scrutiny for some 30 years, the fact that bacteria lose their flagella—and even disable the motor at times—is a recent discovery, independently reported by multiple research groups a few years ago.<sup>14–18</sup> One such form of flagellar loss occurs during starvation. Because the flagellum is an energetically expensive nanomachine, bacteria may eject their flagellar filaments, including hooks, when they encounter an environment with sparse nutrients.

Interestingly, on ejecting the extracellular protrusions, the motor is partially disassembled, and only the bushing rings remain as a relic in the outer membrane, readily observable using cryo-ET. Whereas the bushings appear to be hollow when surrounding the driveshaft before the flagellar loss, they become plugged when the relic rings are left behind. The process of flagellar loss is observed throughout a vast variety of bacterial species, suggesting that it is inherent to flagellar motors. Thus, in addition to acting as bushings during the course of normal operation, the plugged bushing rings may play a significant role in keeping the membrane intact by sealing up the hole following a flagellar loss event under starvation conditions.<sup>14</sup>

The process of ejecting the extracellular protrusions and forming the bushing ring plug, however, is not the only way by which bacteria can lose their flagella and disable the motor. For instance, it has been demonstrated that under severe stress, such as cell disintegration, the motor can lose its C ring,<sup>15</sup> which suggests a weak interaction between the C ring and the rest of the motor.

One spectacular flagellar-loss process occurs in the microbial predator *Bdellovibrio bacteriovorus*. To consume other bacteria, it enters the periplasmic space between the prey's inner and outer membranes. As shown in figure 5, on capturing prey, the predator retracts its extracellular flagellar filament and hook into its own periplasmic space.<sup>16</sup> Ultimately, the retracted flagellum is, presumably, digested. It is tantalizing to think that the retraction process, which implies the resorption of the filament back into the periplasm, may have had an important role

in the evolution of the unique periplasmic endoflagellum in spirochaetes.

## Evolving molecular nanomachines

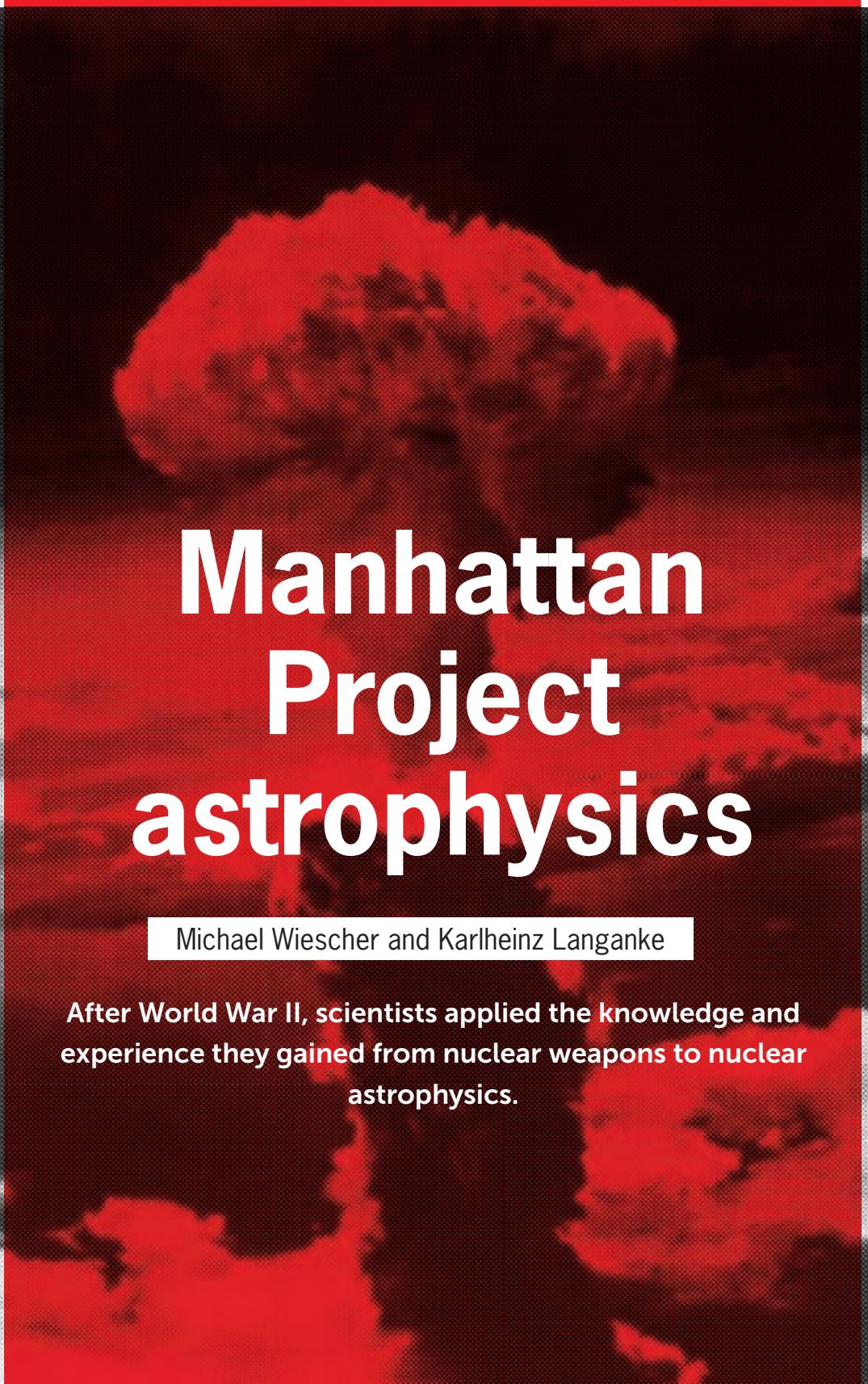
Humans have always been fascinated by both the smallest- and largest-scale worlds. In Jonathan Swift's classic *Gulliver's Travels*, Gulliver encounters both worlds in his voyages to Lilliput and Brobdingnag. And now techniques such as cryo-ET have transformed the invisible world of microbes into a Lilliputian environment for researchers, much the same way that observatories and telescopes have transformed the phenomena in outer space into beautiful worlds for astronomers. The propeller-like motion driven by the flagellar motor is but one form of motion used by microbes because different species are known to propel themselves in different ways by using various molecular nanomachines. For example, some cells use another set of nanomachines known as pili, hair-like appendages that extend and retract to pull the cell over surfaces. Other bacteria glide by moving thin protein filaments that protrude from the cell on special periplasmic tracks using motors embedded in the cell membranes.

Studying the diverse range of nanomachines and macromolecular structures that enable bacterial motility in greater detail and how they assemble, disassemble, and function sheds light on their evolution. In fact, a similar approach has been used to reconstruct life history from the fossil record. It is said that on the sight of a single bone relic, or even a single piece of a bone, Georges Cuvier, the founding father of paleontology, could "recognize and reconstruct the portion of the whole from which it would have been taken." During the growth of a human embryo, many developmental stages reflect vestiges of the evolutionary history of *Homo sapiens*, such as the development of embryonic tail-like structures and pharyngeal arches. Similarly, the assembly intermediates and disassembly relics of macromolecular nanomachines keep traces of their past and help scientists reconstruct their history.

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# Manhattan Project astrophysics

Michael Wiescher and Karlheinz Langanke

**After World War II, scientists applied the knowledge and experience they gained from nuclear weapons to nuclear astrophysics.**

**Michael Wiescher** (wiescher.1@nd.edu) is the Frank M. Freimann Professor of Physics at the University of Notre Dame in Indiana. **Karlheinz Langanke** is the former research director at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany.



# A

much-noted side issue in director Christopher Nolan's 2023 movie *Oppenheimer* is the possibility that detonating a bomb by nuclear fission would release so much energy that it could cause a fusion chain reaction in the atmosphere. That fear was raised and spread by Edward Teller (shown in figure 1) among concerned scientists during a 1942 meeting at the University of California, Berkeley.

The scientists thought that a fission bomb's detonation could so rapidly heat the atmosphere that its temperature might reach a point at which the fusion of nitrogen-14 nuclei would occur. They also considered a second possibility—that of fusion between  $^{14}\text{N}$  and hydrogen-1 from water vapor in the atmosphere. Hans Bethe, head of the theory division at the Los Alamos Laboratory, estimated the probability for a chain reaction as very low.

J. Robert Oppenheimer, portrayed in figure 2, discussed that obvious danger with Albert Einstein in the movie but didn't go into the physical details. An actual meeting between the two would have been unlikely because Einstein was little versed in questions of nuclear reactions and the mechanisms behind quantum mechanical fusion. In reality, Oppenheimer traveled by train from Berkeley to Chicago in the summer of 1942 to talk about the issues with Arthur Compton.

At the time, Compton was head of the metallurgical laboratory at the University of Chicago, which was responsible for developing reactors to breed plutonium-239. He was also the leading expert in photon scattering and the cooling of highly heated atmospheres. When Oppenheimer arrived, Compton picked him up at the train station and they drove to Compton's vacation home on Otsego Lake in Michigan, where they discussed the question. As Compton later recalled in his book *Atomic Quest*, they concluded that further experiments would be necessary to confirm that a thermal runaway would not happen at atmospheric conditions.

Bethe's estimates indicated that neither the temperature nor pressure expected during the detonation of the first fission bomb, codenamed the Trinity test, would be high enough to ignite the atmosphere. But no experimental data existed on the relevant reaction probabilities, or fusion cross sections, so such

an ignition could not be deemed impossible. The Trinity test took place in July 1945, and the atomic bombs were dropped on Hiroshima and Nagasaki shortly thereafter. Despite the bombs' tremendous damage, they did not set the atmosphere on fire.

## Theory mitigates fear

The year after the test, Teller, his graduate student Emil Konopinski, and local technician Cloyd Marvin Jr wrote a classified Los Alamos National Laboratory report in which they summarized theoretical considerations on the possible ignition of the atmosphere by an atomic explosion.<sup>1</sup> The paper, declassified in 1979, argues that propagation of nuclear burning in the atmosphere is possible only if the energy gained from nuclear reactions is greater than the energy loss through the emitted gamma and beta radiation.

Konopinski, Teller, and Marvin considered the fusion of two  $^{14}\text{N}$  nuclei as the most important energy-producing reaction, because  $^{14}\text{N}$  is the dominant component in Earth's atmosphere. On the other hand, when compared to the stable oxygen-16 isotope,  $^{14}\text{N}$  nuclei can easily be broken up. Therefore, the fusion of two  $^{14}\text{N}$  atoms should lead mainly to a rearrangement of the nucleons by the nuclear force and produce a light fragment and a heavy fragment. Energetically, the most favorable result would be their breakup into alpha particles and a magnesium-24 nucleus.

Up to 17.7 MeV of kinetic energy from the reaction can be transferred to the emitted alpha particles. Teller and coworkers approximated the cross section from the geometrical size of the  $^{14}\text{N}$  nuclei and corrected for the energy dependence by multiplying it by the quantum mechanical probability for tunneling through the deflective Coulomb potential between the two positively charged nitrogen nuclei.

Distributing the initial alpha-particle energy is most efficient in collisions with similarly heavy particles and much less efficient for electrons. Therefore, a uniform distribution of nuclear fragments characterized by the nuclear temperature  $T_n$  can be quickly established. Although the electron-gas temperature is much lower, it can also be calculated as a function of  $T_n$ .



**FIGURE 1. EDWARD TELLER.** Although he may have worried about the potential danger of the sudden energy release from fission-triggered fusion reactions between abundant nitrogen-14 nuclei in the atmosphere, Teller argued for such reactions to enhance the power of nuclear weapons. (Illustration by David McMacken.)



**FIGURE 2. J. ROBERT OPPENHEIMER** in typical postures—at the blackboard and with a cigarette. His goal as scientific director of the Manhattan Project was to develop a nuclear device that exploded from the fission of uranium-235 and plutonium-239. (Illustration by David McMacken.)

The electron gas cools by inelastic scattering and by emitting bremsstrahlung in the form of a continuous x-ray spectrum. Because the atmosphere is transparent to that radiation, it loses energy. Konopinski, Teller, and Marvin found that the rate of energy loss is always greater than the rate of its production by nuclear fusion. So the critical condition needed to ignite the atmosphere cannot occur.

To capture the result quantitatively, the three scientists calculated the energy generation and radiation cooling as a function of temperature, plotted in figure 3. They defined the ratio of the rate of energy loss to its production as the "safety factor." The figure demonstrates that the safety factor decreases at high temperatures as the energy-production curves level off. The report's abstract points out that in the case of more powerful fission bombs, however—or even the fusion bombs that Teller had envisioned for the future—the potential danger of an ignited atmosphere remains:

The energy losses to radiation always overcompensate the gains due to reactions. . . . It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration.<sup>1</sup>

That passage reflects Teller's foresight: The weapons community, including Oppenheimer, expected the development of more powerful fission bombs, and Teller saw the need to develop thermonuclear fusion weapons orders of magnitude more powerful.

Despite Bethe's reassurances, the fear of an atmospheric chain reaction remained a concern throughout the entire nuclear weapons test program. The 10-fold and higher increase in a fission bomb's energy release—from the 20-kiloton Trinity test (see figure 4) to the 200-kiloton Hutch underground test in the Nevada desert in 1969 and more—reduced the estimated safety margin. (The magnitudes of bombs are expressed in kilotons of TNT needed to produce a comparable explosion.)

The reduction was greater when scientists began underwater tests, which involved higher densities and more hydro-

gen content. Of even more concern were the tests of 20-megaton thermonuclear weapons (so-called hydrogen bombs), and scientists even considered the possibility of the fusion of  $^{16}\text{O}$  atoms in ocean water.<sup>2</sup> Their explosions would increase the sudden energy release by up to three orders of magnitude. The uncertainties in the initial crude energy release and cooling calculations required experimental verification.

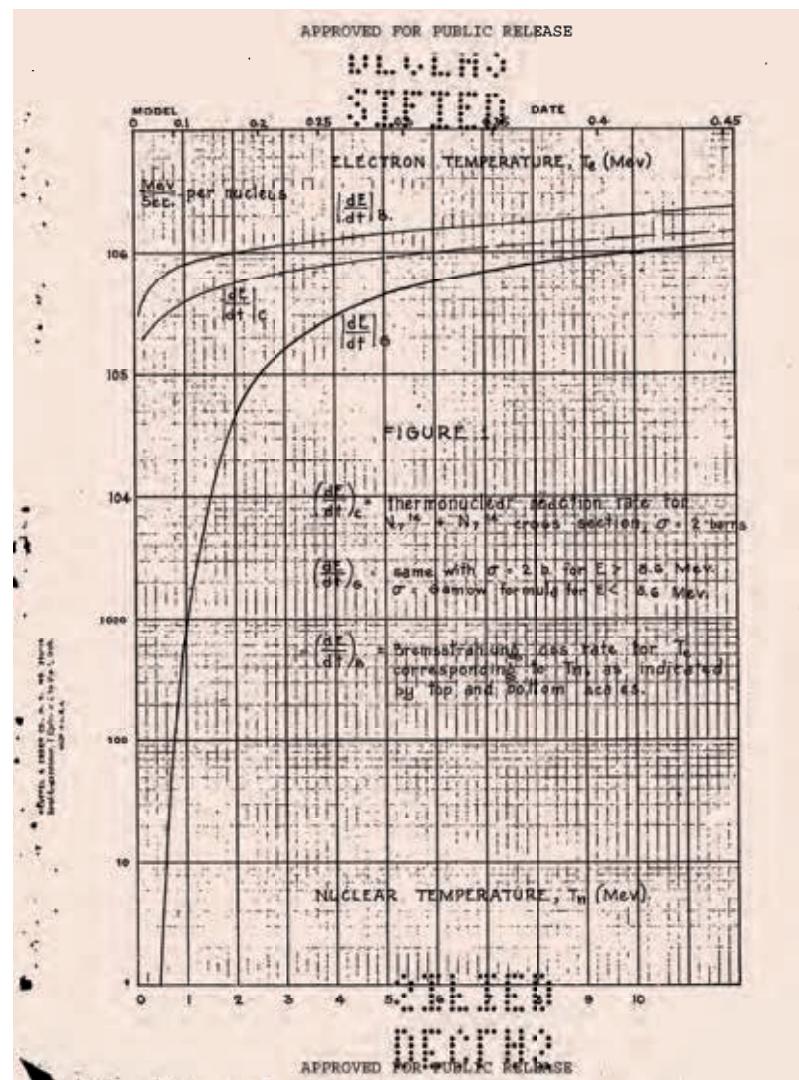
## Experiment confirms theory

To experimentally clarify the troubling situation, a dedicated accelerator was built at Oak Ridge National Laboratory in the early 1950s, which made it possible to measure fusion cross sections for  $^{14}\text{N} + ^{14}\text{N}$ ,  $^{16}\text{O} + ^{16}\text{O}$ , and other reactions of medium-heavy nuclei.<sup>3</sup> Alexander Zucker, one of the young scientists who was to measure the effective cross sections and who would later be director of Oak Ridge, noted that for security reasons he and other experimentalists were not directly told why there was interest in those data.

After the detonation of the Soviet 50-megaton “Tsar Bomba” in 1961 above Novaya Zemlya—a group of islands in the Arctic Circle—it became experimentally clear that the conditions required for atmospheric (or even oceanic) ignition had not been reached. (And that remains the case today.) The experimental measurements obtained by Zucker and others demonstrated that the fusion probability is smaller than the geometric cross section assumed by Teller and his coworkers. Because the atmosphere is heated only to temperatures of a few million degrees, the energies of the fusing nuclei—a few hundred kiloelectron volts—are well below the Coulomb barrier, and the likelihood of fusion is low.

The Oak Ridge fusion tests were not confined to nitrogen and oxygen nuclei; they also included tests on light isotopes such as deuterium and tritium and were meant to inform Teller’s plans and ideas for developing the “Super,” his label for a thermonuclear weapon based on fusion. The idea for the fusion bomb based on the fusion of deuterium and tritium isotopes was born out of prewar ideas and papers on hydrogen burning of the sun, but those deliberations triggered the fear of nitrogen burning in the atmosphere.

Konopinski and Teller had published in 1948 the first theoretical prediction for the fusion probability of two deuterium nuclei,<sup>4</sup> envisioned as bomb fuel. Those calculations were based on existing prewar measurements of the reaction, which were soon supported by experimental studies at Los Alamos. Because of the much lower Coulomb barrier between the two deuterium nuclei, lower temperatures were necessary to trigger the fusion than in the case of nitrogen nuclei. That realization motivated the development of the two-step design of the hydrogen bomb. The first step—the ignition of a plutonium bomb—generated the necessary temperature and density con-



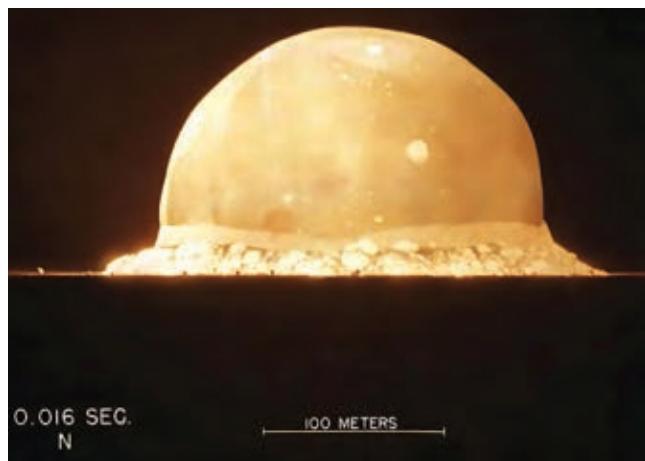
**FIGURE 3. A CRITICAL PLOT** of the rate of energy production as a function of temperature (in megaelectron volts), from the originally classified 1946 Los Alamos report *Ignition of the Atmosphere with Nuclear Bombs*.<sup>1</sup> Three curves characterize the energy-transport conditions for different temperatures in the nuclear fireball. The  $(dE/dt)_c$  curve shows the reaction rate for the fusion of two nitrogen-14 nuclei when a constant cross section is assumed. The  $(dE/dt)_G$  curve shows the  $^{14}\text{N} + ^{14}\text{N}$  fusion reaction rate when the cross section is assumed to rapidly decrease at low energies, as predicted by George Gamow. And the  $(dE/dt)_B$  curve shows the radiative energy loss through x-ray emission, as predicted by Arthur Compton. (From ref. 1.)

ditions required to trigger the second step, the fusion of deuterium fuel.

Those million-degree temperatures are similar to ones found in the late hydrostatic burning stages of massive stars. That area of nuclear astrophysics, involving the last stages of stellar burning through the fusion of light elements, received an important impetus from the work done on the Manhattan Project and vice versa.

## Astrophysics influences bomb physics

When the Manhattan Project was striving to develop a fission bomb, it was no coincidence that some of its protagonists, including Teller, were interested in questions of fusion. He had



**FIGURE 4. THE TRINITY FIREBALL**, 16 ms after ignition. That's the moment of maximum energy release and localized heating of the atmosphere during the first nuclear weapon test. The fireball's opacity prevented radiative energy loss, so the released heat was contained within the fireball. The lightly tinted spots on the fireball's surface are locations where radiation emission would occur first. (Courtesy of the US Department of Energy.)

been investigating a similar astrophysical question in the 1930s: How can stars generate the energy that allows them to shine and yet remain in a state of equilibrium for long periods of time?

The method for calculating the energy-dependent effective cross sections that Teller had used to estimate the likelihood of atmospheric ignition had been developed by George Gamow,<sup>5</sup> who was a fellow professor at George Washington University (GW) between 1935 and 1941. Gamow had left the Soviet Union for political reasons in 1933, and Teller, who was Hungarian and Jewish, came to the US in 1935 after leaving Germany two years earlier to escape the Nazi movement. Both men were interested in questions of energy production in stars, a topic that connected them with Carl Friedrich von Weizsäcker, one of Teller's fellow students in Germany.

Gamow organized annual meetings at GW on the new questions in theoretical physics. The topic of the fourth Washington Conference on Theoretical Physics, in 1938, was the importance of nuclear physics for astrophysics, and scientists discussed the possibilities of nuclear reactions and chain reactions in stars. Bethe, another Jewish refugee from Nazi Germany, presented his ideas on hydrogen burning in stars. Weizsäcker was pursuing those ideas as well. And Gamow, knowing both of them, acted as contact and mediator between the theorists and their ideas during the years before the war.<sup>6</sup>

To calculate the fusion rates in their 1946 report, Teller and coworkers used the overlap integral between the Maxwell-Boltzmann distribution of the velocities of nitrogen nuclei and their effective cross section. That methodology had first been used in 1938 by Gamow and Teller to calculate reaction rates for evaluating stellar burning.<sup>7</sup> Independently Bethe also used the approach to calculate the important fusion reaction rates between light nuclei that drive the energy generation of the Sun. The methodology gave rise to the standard formalism for presenting nuclear reaction rates in any kind of high-temperature environment—from bomb to star.

The fifth Washington Conference on Theoretical Physics, in 1939, was overshadowed by news of Otto Hahn and Fritz Strassmann's discovery of nuclear fission, as interpreted and explained by Lise Meitner and Otto Frisch. Even before joining the Manhattan Project in 1943, Teller saw the potential applications for his experience in fusion physics and reaction-rate calculations and began to tirelessly promote nuclear fusion as a possibility for the bomb. His calculations excluded the fusion of heavier ions; the fusion of light deuterium or tritium isotopes seemed to be much more promising. The problem was the inability to produce the appropriate amount of fuel material.

Although the calculation of nuclear reaction rates in hot environments was a necessity for astrophysics, the Manhattan Project provided the opportunity to develop the theoretical methodology with which to treat nuclear reactions and thus calculate previously unknown reaction rates.

## Feedback for astrophysics

After the war, when most of the physicists had returned to their university chairs and research institutes, the experience they had gained by simulating nuclear processes in a bomb explosion served to develop new ideas in nuclear astrophysics. Bethe returned to Cornell University, where he worked with his student Edwin Salpeter, a Jewish emigrant from Austria. They demonstrated that proton-proton chains, the sequence of nuclear reactions by which stars convert hydrogen into helium, are the main energy source of our Sun. The reaction sequence containing light-element fusion processes, such as  $^2\text{H} + ^2\text{H}$ , were of particular interest for the thermonuclear weapons community around Teller. Predicting new reaction sequences—especially fusion and neutron-induced reactions—was of great interest for understanding the processes that drive stars and bombs alike.

Caltech became the new gathering place for the next generation of young nuclear astrophysicists. On the experimental side, William Fowler, shown in figure 5, made Caltech the international center for astrophysics research. He had been a student, postdoc, and young assistant professor at Caltech before the war, and he knew Oppenheimer well from their prewar history at Caltech. Oppenheimer had impressed Fowler with his report from the 1938 GW conference and Bethe's ideas on the carbon cycle as a key process in astrophysics.

Fowler developed ignition systems for nuclear weapons, including the system that abruptly and symmetrically compressed the plutonium core of the Trinity bomb, causing it to detonate. He was also involved in the development of the bomb initiator—a mixture of polonium-210 and beryllium-9 that would produce a burst of neutrons on demand. Alpha particles emitted by the polonium would be rapidly absorbed by the beryllium, producing carbon-12 and the neutron flux necessary to initiate the chain reaction in  $^{239}\text{Pu}$ . As part of the missile program at China Lake, California, Fowler also considered long-range missile delivery systems for nuclear weapons.<sup>8</sup>

Through his training in experimental nuclear physics at Caltech, Fowler became quite familiar with the issues of low-energy nuclear reactions. In 1951 he was appointed the scientific director of Project Vista at Caltech.<sup>9</sup> The project was established for the development and study of strategic nuclear weapons to defend the US and other NATO countries

against the new, albeit presumed enemy, the Soviet Union. After the project he resumed his role in academia, again taking up his research in nuclear astrophysics.

That move was motivated by Cambridge University's Fred Hoyle.<sup>10</sup> In collaboration with the astronomers Margaret Burbidge and Geoffrey Burbidge,<sup>11</sup> Fowler and Hoyle predicted numerous important reaction sequences for the origin of elements in stars and stellar explosions. Those reactions, in turn, can be traced conceptually to many of the scientific questions posed by the Manhattan Project.

## The science of stars

The Manhattan Project and the subsequent test program—with its associated studies of nuclear reactions at accelerators—also stimulated the progress and development of nuclear astrophysics. It became clear that massive stars, the main producers of elements in the universe, achieve their hydrostatic equilibrium by balancing gravitational attraction against the radiation pressure arising from fusion reactions in the stellar interior. Unlike the stellar atmosphere (and Earth's), stellar matter in the interior is not transparent to radiation.

Energy transport by radiation is important for stars, but it proceeds rather slowly. In the Sun, for example, it's on a time scale of millions of years. As a consequence of the slow energy loss, a star can establish an equilibrium of nuclei, electrons, and radiation—all of them having the same temperature.

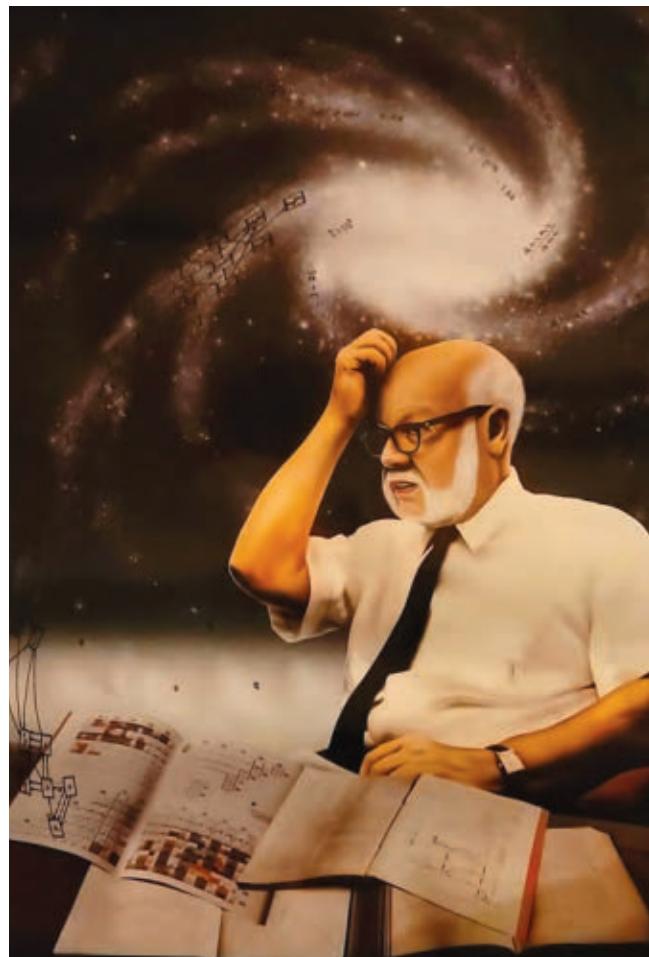
Hydrogen- and helium-induced reactions were being studied at Caltech and Cornell. For Manhattan Project scientists,  $^{14}\text{N}$  was the isotope of most concern. It plays a key role in the Bethe–Weizsäcker carbon–nitrogen–oxygen cycle of hydrogen burning and becomes enriched in the process. Before the 1950s some suggested that the enrichment might make subsequent  $^{14}\text{N} + ^{14}\text{N}$  fusion important in stars. But when researchers considered light fusion reactions as an alternative energy source in the Sun, it became clear that that could not be the case.<sup>12</sup> The phases after helium burning in massive stars proceed via carbon ( $^{12}\text{C} + ^{12}\text{C}$ ) and oxygen ( $^{16}\text{O} + ^{16}\text{O}$ ) fusion.

Those fusion reactions dominate the final years in the life of a massive star. And through the release of protons, neutrons, alphas, and an intense flux of high-energy photons, a complicated network of different nuclear reactions emerges, producing heavy elements up to iron and nickel. In that mass region, nuclear fusion vanishes as a stellar energy source, and the star's core collapses under its own weight. The collapse triggers a supernova explosion that releases many of the nuclei produced during the star's life. The physics of the supernova explosion was Bethe's focus during the last decades of his life. The final product of the explosion is either a neutron star consisting of extremely dense nuclear matter or a black hole. The mass of neutron stars was first estimated in 1939 by Oppenheimer and his student George Volkoff.<sup>13</sup>

Theoretical and experimental studies associated with the Manhattan Project and subsequent developments thus have largely informed the nuclear astrophysics community's effort to understand and interpret the development and life of stars—from their beginning as low-density interstellar dust to their end.

## The test program's impact

In addition to providing insights into the physics of fusion



**FIGURE 5. CALTECH'S WILLIAM FOWLER**, best known for his work on stellar nucleosynthesis. The processes he considered probably came from the analysis of nuclear reaction data that were measured at the institute's Kellogg Radiation Laboratory and deduced from bomb debris during the nuclear weapons test program. (Courtesy of Caltech, Symposium on Nuclear Astrophysics: A Celebration of Willy Fowler, 14–16 December 1995.)

reactions between charged nuclei, the observations and calculations from the nuclear weapon test program have opened a new path to understanding neutron-reaction physics, the existence of which was revealed by analyses of materials from the test program. With his knowledge of neutrons as the initiators of plutonium-bomb explosions, Fowler recognized the possibility of similar alpha-induced neutron sources in stars. In 1937 Weizsäcker was the first to predict neutron-capture processes as a way to produce the heavy elements observed in nature. And on the basis of the formalism developed by Gamow and Teller, Fowler and his co-workers later calculated the reaction rates for neutron-induced processes.<sup>14</sup>

Fowler's effort was further motivated by the discovery of the heavy elements fermium (atomic number 100) and einsteinium (atomic number 99) deposited on the corals of the Enewetak Atoll in the Marshall Islands and in the filters of an observation aircraft after the first hydrogen-bomb test, Ivy Mike, in 1952. Those discoveries led to the first thoughts on the rapid neutron

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capture, known as the r-process in type Ia supernovae.<sup>15</sup>

Those thoughts, however, turned out to be hasty. After long-lived transuranic elements were identified in the debris of the 1964 Par and Barbel tests, Hoyle and Fowler expanded their model of the r-process to core-collapse supernovae.<sup>16</sup>

Returning to the initial question of atmospheric reactions between <sup>14</sup>N isotopes in our atmosphere, one reaction was not considered in the original analysis by Konopinski, Teller, and Marvin: The enormous neutron flux released by fission did indeed lead to an interaction with atmospheric <sup>14</sup>N, yielding <sup>14</sup>C. That reaction is naturally triggered by the steady bombardment of the atmosphere by cosmic rays; the enormous release of neutrons by a nuclear bomb explosion only multiplies the effect.

The long-lived <sup>14</sup>C, or radiocarbon, that was produced by nuclear tests is clearly seen in the so-called radiocarbon bomb peak—a doubling of the relative isotopic concentration of <sup>14</sup>C in the atmosphere in the 1960s. Radiocarbon in our atmosphere did decrease rapidly, because through the biological carbon cycle the isotope is absorbed by plant materials and remains in biological materials for thousands of years. The bomb peak today enables a wide range of analytical studies using the radiocarbon method.<sup>17</sup> Thus, radiocarbon that remains in our bodies is a long-lasting sign of the nuclear weapons hubris that Oppenheimer tried to warn us against.<sup>18</sup>

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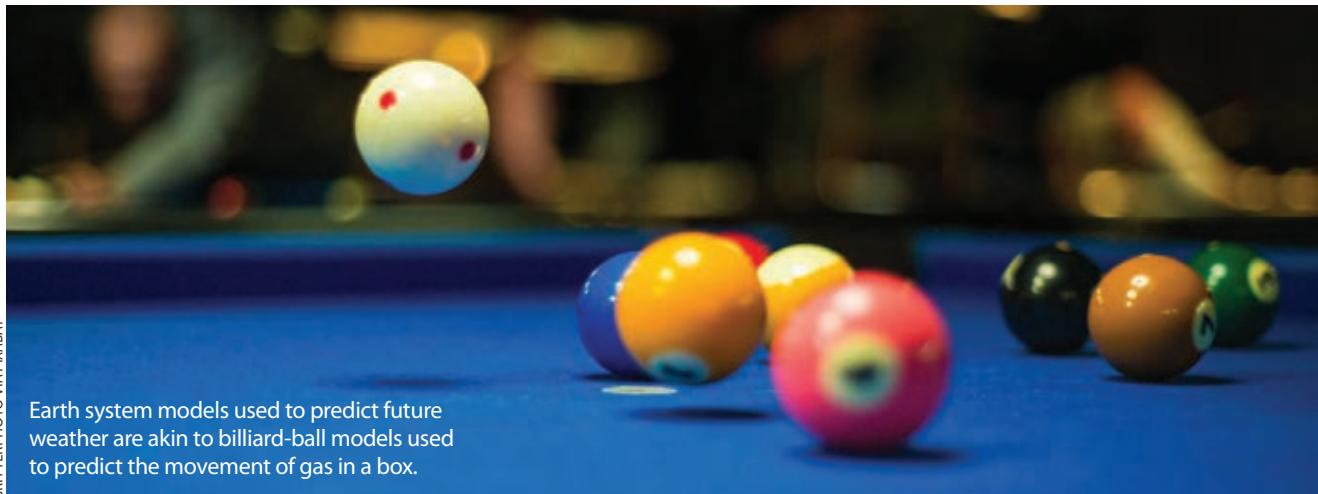
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Earth system models used to predict future weather are akin to billiard-ball models used to predict the movement of gas in a box.

## Disillusionment with climate models

**D**avid Stainforth's ambitious book *Predicting Our Climate Future: What We Know, What We Don't Know, and What We Can't Know* spans a vast territory, starting from the philosophical and scientific underpinnings of supercomputer climate models to an assessment of the economic, social, and policy implications of climate change. It is an insider's reflection on 30 years of climate modeling and policy.

Opening chapters cover dynamical-systems concepts, including probability, deterministic chaos, and phase space. To achieve that without equations—and to lighten the prose—Stainforth uses detailed analogies, such as humorous images of kettles, grandfather clocks, tennis balls, and polyhedral dice, with some more successful than others.

Stainforth introduces the reader to today's supercomputer Earth system models. Those are souped-up weather models that might, for example, predict 20 cm of snow in Montreal on the morning of 18 December 2099. Since Earth system models are sensitively dependent on small-scale initial conditions, they are chaotic and interpreted probabilistically. The Earth system models used in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) currently have hourly resolutions and must be averaged over 100 000 time steps to yield the reports' decadal projections.

Statistical physicists may be troubled

that supercomputers are tasked with calculating so many details that are already known to be irrelevant, yet for Stainforth, the real problems lie elsewhere. He cites three: poorly known macroscale initial conditions, such as today's climate state; tuning bias; and the status of multimodel ensembles.

If an Earth system model is akin to the billiard-ball model of a gas in a box, for which the aim is to predict the positions and velocities of the balls at some later time, then the macroscale initial conditions are the gas's temperature, density, and other variables. Today's poorly constrained macro-initial climate state invites compounding uncertainties in the chaos-induced probabilities.

Tuning bias is a consequence of the Earth system model itself being ill defined. It arises because of many numerical approximations in the underlying physics. In his book, Stainforth describes a numerical experiment on an Earth system model that has 21 such parameters, and in principle, each parameter must be reevaluated after any model updates or changes.

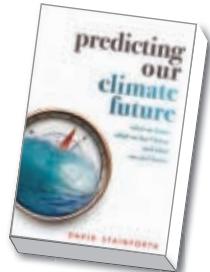
The IPCC's scenario-based predictions use multimodel ensembles compiled from approximately 40 Earth system models, each of which was built by a different team but uses the same "scenarios" or assumptions about future human behavior, especially about future greenhouse gas emissions. The uncertainty bounds—the confidence limits—

### Predicting Our Climate Future

**What We Know, What We Don't Know, and What We Can't Know**

**David Stainforth**

Oxford U. Press, 2023. \$24.95



in the IPCC's multimodel-ensemble "projections" are simply quantifications of the differences between the different Earth system models.

As the book progresses, Stainforth's disenchantment with current climate models becomes evident. The classic Earth-system-models approach is indeed in crisis, and Stainforth is in growing company. He, along with colleagues, suggests replacing probabilistic climate projection frameworks with subjectively evaluated sequences of events, or storylines. Other disenchanted colleagues variously prefer using artificial intelligence or machine learning to make projections.

To understand the disenchantment, one needs to look at a key climate parameter: the amount that the temperature will increase following a doubling of atmospheric carbon dioxide. Although for decades the uncertainty has been fairly large, the experts and the models had always been closely aligned. Now experts have converged around a much smaller temperature range, yet the members of the IPCC's new multimodel ensemble are—for the first time—diverging

from each other, yielding a wider temperature range and an increased uncertainty. Today the experts are confident that they know better than the models.

The last part of the book discusses the human side of climate change; determining future warming is only the first step in dealing with the climate crisis. We need to evaluate the social, economic, and environmental consequences of a warmer planet. Stainforth summarizes some of the contentious results of mainstream economists; he not only underlines the wide divergences among them but also stresses how even a small change in the predicted warming drastically changes the damage estimates.

In *Predicting Our Climate Future*, Stainforth lists many factors for the divergences, perhaps the most important of which is the choice of discount rate, which is used to express the costs of future climate damage in terms of today's currency. A typical discount rate of 6%—advocated by the economist William Nordhaus—would put the cost of avoiding \$200 trillion of climate damage in the year 2100 at a mere \$2 trillion today. If we really care for our children, we should instead follow Nicholas Stern in his 2006 report on the economics of climate change and use a much lower rate: Stainforth discusses a discount rate of 0.1%, while Stern used an average rate of 1.4%. Using the latter rate yields \$72 trillion today, comparable to the global GDP, and it led to Stern being accused of making “fear-mongering arguments” in a *Wall Street Journal* editorial.

Stainforth does an admirable job navigating the wide-ranging and technically demanding material, yet statistical physicists may have reservations. Why forecast the weather to the year 2100 when the goal is a decadal average? Why care about the positions and velocities of the particles in a box if all you want is the macroscopic pressure or temperature? Indeed, an entire historical strand of fluid mechanics and atmospheric sciences—turbulence theory—is dedicated to elucidating the relevant higher-level statistical laws, and that neglected strand has already started to evolve with new stochastic models that substantially reduce uncertainties. Still, for those interested in an introduction, Stainforth's book is a useful place to start.

**Shaun Lovejoy**

(*lovejoy@physics.mcgill.ca*)

McGill University

Montreal, Quebec, Canada

## NEW BOOKS & MEDIA

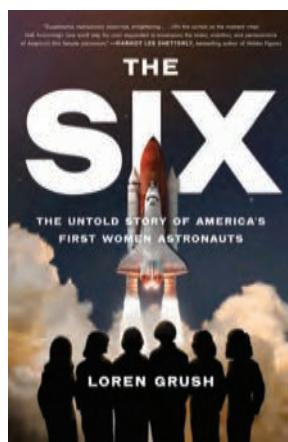
### The Six

#### The Untold Story of America's First Women Astronauts

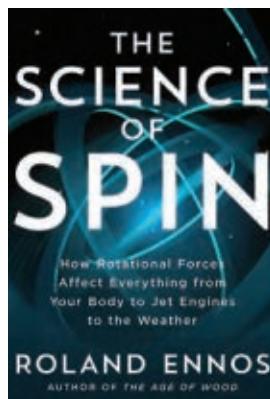
**Loren Grush**

Scribner, 2023. \$32.50

In 1978 NASA accepted six women into its previously all-male astronaut corps: Sally Ride, Judy Resnik, Kathy Sullivan, Anna Fisher, Margaret “Rhea” Seddon, and Shannon Lucid. *The Six* tells the inspiring story of the women's journeys up to entering the astronaut program, their experiences once they were admitted, and the pioneering missions that made them the first US women to fly into space. According to the author's note, as part of her research, science reporter Loren Grush conducted more than 100 hours of interviews, consulted archival documents, and reviewed audio and video footage of old interviews and press conferences. The result is a vivid, blow-by-blow account of a groundbreaking period in history.



—cc



### The Science of Spin

#### How Rotational Forces Affect Everything from Your Body to Jet Engines to the Weather

**Roland Ennos**

Scribner, 2023. \$28.00

In this popular-science book, biologist Roland Ennos sheds light on a fundamental physics principle that he claims has not received the attention it deserves. As Ennos points out, the science of spin “pervades” the world around us. Spin helped form the universe, made Earth habitable, allows humans to walk upright, and is integral to machinery and technology. Yet most people don't really understand how it works. To explain the mechanics of rotation, Ennos eschews mathematical formulas and equations in favor of more intuitive physical explanations of the workings of the universe, human beings, and the machines we've created. The result is a highly approachable book for general readers and scientists alike.

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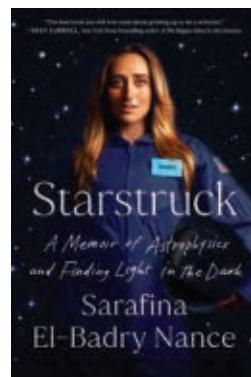
### Starstruck

#### A Memoir of Astrophysics and Finding Light in the Dark

**Sarafina El-Badry Nance**

Dutton, 2023. \$29.00

Long fascinated with the stars, astrophysicist Sarafina El-Badry Nance presents a memoir that blends tales of her educational experiences and family life with observations about the universe. Growing up in Texas in the 1990s and 2000s with an American father and Egyptian mother, Nance battled racism, sexism, her parents' marital strife, and her own insecurities to pursue her dream of becoming an astronomer. But even after gaining entry to the graduate astronomy program at the University of California, Berkeley, she found that life had thrown her yet another curveball—she'd inherited her father's cancer gene, which prompted her to undergo a double mastectomy. Despite the heavy subject matter, *Starstruck* is engaging and inspirational.



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# NEW PRODUCTS

## Focus on photonics, spectroscopy, and spectrometry

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](mailto:ptpub@aip.org).

**Andreas Mandelis**



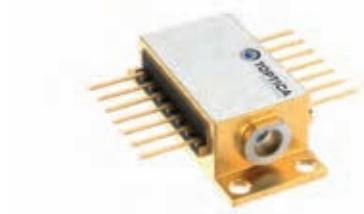
### Flexible spectrometer

Offering higher performance than its predecessors, the Varius spectrometer now available from Avantes is designed to meet the needs of a wide variety of applications. The Varius is offered in two product variations: One has either a 2048- or

a 4096-pixel detector, USB 3 high-speed data transfer, and a replaceable slit to customize throughput and resolution. The other, the industrial OEM version, has a stainless steel electromagnetic-compatible housing and is optimized for integration into products or systems. The Varius offers superior stray-light performance of 0.1–1% (with a typical value of 300 lines/mm and a blaze 300 nm at less than 0.3%); a high signal-to-noise ratio of 375:1 and 365:1, respectively; and a symmetrical Czerny–Turner optical bench design. Its wavelength range is 190–1100 nm and its dynamic range is 4500. Applications include use in research laboratories, radiometry, thin-film-coating deposition, semiconductors, leaf measurement, and chlorophyll analysis. *Avantes BV, Oude Apeldoornseweg 28, 7333 NS Apeldoorn, the Netherlands, [www.avantes.com](http://www.avantes.com)*

### Direct-injection mass spectrometry

Syft has unveiled its selected-ion flow-tube mass spectrometry (SIFT-MS) technology, Syft Tracer. According to the company, the innovation in direct-injection MS offers advancements in sensitivity, performance stability, reproducibility, and repeatability. It is suitable for use in the various analytical applications and industries that require fast time to data, high throughput, and continuous operation. SIFT-MS applies precisely controlled chemical ionization reactions to detect and quantify trace amounts of volatile organic compounds and inorganic gases. It delivers real-time, chromatography-free direct analysis of compounds that traditionally require intensive sample preparation, including even complex matrices and high-humidity samples. It analyzes compounds that cannot be easily targeted by traditional chromatographic methods, such as formaldehyde, hydrogen sulfide, ammonia, ethylene oxide, and nitrosamines. SIFT-MS is designed to be accessible to nontechnical users and generates data that are easy to interpret. *Syft, 68 St Asaph St, Christchurch 8011, New Zealand, [www.syft.com](http://www.syft.com)*



### Laser diodes at 670 nm

Toptica Eagleyard has announced that its miniTA (tapered amplifier) and miniECL (external cavity laser) diodes are now available at 670 nm. Housed in a new, optimized hermetically sealed butterfly package, the miniTA has 14 thick pins to enhance the power supply. It now comes with an evaluation board. Like other laser diodes in the product family that emit different wavelengths, the 670 nm miniTA features integrated thermal management and beam collimation. High optical single-mode power up to 1 W and high amplified spontaneous emission suppression make it suitable for applications such as spectroscopy, quantum technologies, the life sciences, and atomic clocks. The single-frequency 670 nm miniECL has a 40 mW output. Because of its hermetically sealed package, the miniECL is robust and typically has a super-fine linewidth of 100 kHz for high precision. Wavelengths between 650 and 1100 nm can be customized upon request. The integrated beam collimation, thermoelectric cooler, and thermistor contribute to ease of use. The miniECL is suitable for use in spectroscopy, quantum technologies, metrology, the life sciences, and atomic clocks. *Toptica Eagleyard, Rudower Chaussee 29, 12489 Berlin, Germany, [www.toptica-eagleyard.com](http://www.toptica-eagleyard.com)*



### Time-correlated single-photon counter

PicoQuant has developed the PicoHarp 330 event timer and time-correlated single-photon counting unit for state-of-the-art photonics research. Made for applications with up to three channels, the PicoHarp 330 offers flexible channel configuration and synchronization and supports a wide variety of single-photon detectors. Users can choose between edge triggers and constant-fraction

discriminators. The PicoHarp 330 is equipped with either one or two identical synchronized yet independent detection channels, providing the choice between 1 + 1 or 1 + 2 channels for input and synchronization purposes. It offers a time resolution of 1 ps and high timing precision of 2 ps rms/channel, with 3 ps rms between channels. High data throughput via the USB 3 interface allows count rates of up to  $85 \times 10^6$  counts/s/channel. Because of the ultrashort dead time of 680 ps, multiple photons can be detected per cycle. The PicoHarp 330 features 65 536 histogram bins/input channel, with a minimum width of 1 ps. Over  $4 \times 10^9$  counts (32 bits) can be collected per bin. *PicoQuant, Rudower Chaussee 29, 12489 Berlin, Germany, [www.picoquant.com](http://www.picoquant.com)*

### Submicron IR particle spectroscopy

The featurefindIR automation solution from Photothermal Spectroscopy performs precise, rapid spectroscopic measurement of submicron- to millimeter-sized microplastics, contaminants, pharmaceuticals, and other particles in a single measurement session. FeaturefindIR makes optical photothermal IR (O-PTIR) spectroscopic measurements by using various image inputs. Those include single IR wavelength images, cross-polarized bright-field images for improved contrast of smaller features, and fluorescence images. Once the image is captured, featurefindIR's tools allow for precise particle selection based on size, image intensity, and other user criteria. FeaturefindIR's micro-chemical ID report automatically compares hundreds of user-selected spectra against an O-PTIR reference database, reports a hit quality index for each spectrum, and can provide the best chemical ID match for each one. For higher measurement productivity, featurefindIR supports the company's mIRage system's simultaneous IR+Raman measurement capability. *Photothermal Spectroscopy Corp, 325 Chapala St, Santa Barbara, CA 93101, [www.photothermal.com](http://www.photothermal.com)*



### Portable wideband laser

According to SuperLight Photonics, its recently introduced SLP-1000 is the first portable wideband laser. It serves as a smooth, wide-spectral-output light source for spectroscopy and medical and industrial imaging applications. The compact, rugged SLP-1000 is battery operated. It integrates a Menlo Systems seed laser with a Thorlabs-compatible screw thread. Based on the company's Patterned Alternating Dispersion technology, the SLP-1000 offers a high-quality, coherent, and stable spectral output of 400 nm at -3 dB and 1500 nm at -20 dB in the near-IR band at a repetition rate of 100 MHz with pulse durations of around 20 fs. The short pulse duration, owed to the highly efficient supercontinuum generators, allows for the use of lower pulse energies at the generator input. Pulse broadening needed for amplification, noise from amplifier stages, and additional optical components can thus be eliminated. The SLP-1000 provides high-quality nonlinear pulse compression for applications such as third-harmonic surface imaging and transient-absorption spectroscopy. *SuperLight Photonics BV, Brandweerstraat 20, 7514 AE Enschede, the Netherlands, [www.superlightphotonics.com](http://www.superlightphotonics.com)*

### Compact OPO and pump-laser system

Lumibird and GWU-Lasertechnik have released a new model pumping in their Peacock series of optical parametric oscillators (OPOs) and pump lasers on a single platform. The Peacock XT includes a Q-smart-type neodymium-doped yttrium aluminum garnet laser that pumps a state-of-the-art OPO at 355 nm. The whole unit is integrated in a single bench that can easily be inserted into a complex system. The Peacock XT is suitable for users who require a tunable nanosecond-pulsed laser source in the visible and near-IR ranges. It is tunable from 405 to 2850 nm, has fast shot-to-shot wavelength tuning across the entire range, is available in midband or broadband linewidths, and is robust, reliable, and easy to use. With its fully automated wavelength selection, real-time output energy control, and laser-beam-shaping capability, the versatile Peacock XT is appropriate for a wide variety of environments and for demanding applications in the spectroscopy, biotechnology, and medical fields. *Lumibird, 2 rue Paul Sabatier, 22300 Lannion, France, [www.lumibird.com](http://www.lumibird.com)*



### Spectrometer with high dynamic range



The OPAL-Luxe C16736-01 spectrometer from Hamamatsu Photonics has a very high dynamic range of 2 500 000:1 in the spectral range from 200 to 900 nm. To take full advantage of the high dynamic range, the spectral optics have been newly designed with high sensitivity and high wavelength resolution, while minimizing stray light. According to the company, the OPAL-Luxe is particularly effective when strong and weak signals are present simultaneously. Incorporating it into component analyzers that use the light absorption properties of substances in the UV to near-IR region allows for simultaneous analysis of the various components within a sample. Detecting trace amounts of impurities in substances without having to repeat measurements can increase efficiency in the quality control of chemicals. Since it can analyze plasma emissions with high accuracy, the OPAL-Luxe will also help advance plasma application research. *Hamamatsu Corporation, 360 Foothill Rd, Bridgewater, NJ 08807, [www.hamamatsu.com](http://www.hamamatsu.com)*



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**Kent Gee** is a professor of physics at Brigham Young University in Provo, Utah. **Caroline Lubert** is a professor of applied mathematics at James Madison University in Harrisonburg, Virginia. **Michael James** is a managing partner and chief engineer at Blue Ridge Research and Consulting LLC in Asheville, North Carolina.



## The roar of a rocket

Kent L. Gee, Caroline P. Lubert, and Michael M. James

During a rocket's liftoff, its extreme sound levels can damage launch structures, payload electronics, and even the rocket itself.

**T**o say that rockets are loud is an understatement. Few of them are as loud as were NASA's 1970s-era Saturn V rockets. Its engines generated 45 GW of mechanical power while burning a combined 12 700 liters of kerosene and liquid oxygen every second. The stakes were high. Saturn V rockets carried Apollo astronauts to the Moon and the Skylab space station into orbit.

Thankfully, less than 1% of a rocket's mechanical power is converted into sound. Even so, the Saturn V radiated nearly 250 MW of sound power. By comparison, a typical gas-powered lawnmower radiates a few tens of milliwatts. It would take around 10 billion lawnmowers to equal the acoustic power of the Saturn V.

Although the number of rocket launches is rapidly increasing each year, only about 220 of them took place in 2023. Compare that number with commercial aviation, which sees 25 000 flights per day in the US alone. But each rocket launch has the potential for far greater impact.

Rockets produce sound waves of sufficient intensity to induce vibrations capable of damaging the rockets themselves, their payloads, and nearby launch-pad structures. Farther afield, a rocket's predominantly low-frequency noise propagates much longer distances than aircraft noise, such that community and environmental noise concerns are different, but researchers have not yet developed techniques to quantify how people and animals react to rocket noise. The overall noise footprint and damage risk will also increase as global demand for space access surges from the emerging industry of

suborbital tourism (see the Quick Study by Jonathan McDowell, PHYSICS TODAY, October 2020, page 70).

This Quick Study describes a rocket's noise-generation physics and discusses the impacts of that noise.

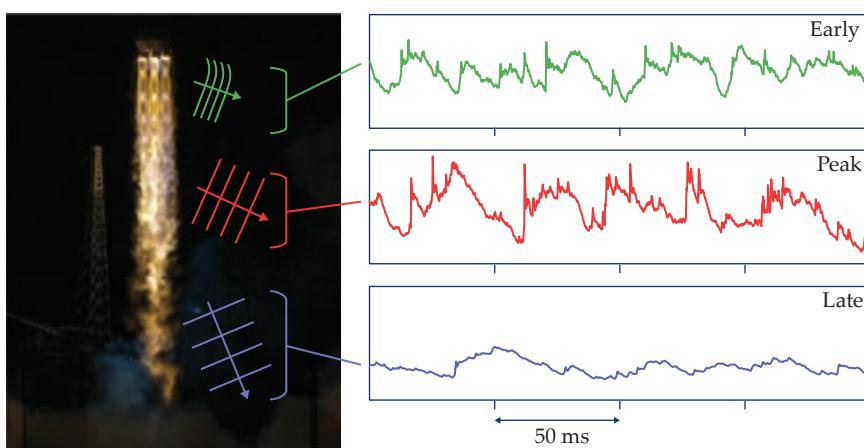
### Power and pressure

Sound is quantified in terms of decibels, which translate SI units—watts for power and pascals for pressure—into a condensed, logarithmic measurement scale. Sound power is an integration of the radiated sound across all angles and frequencies.

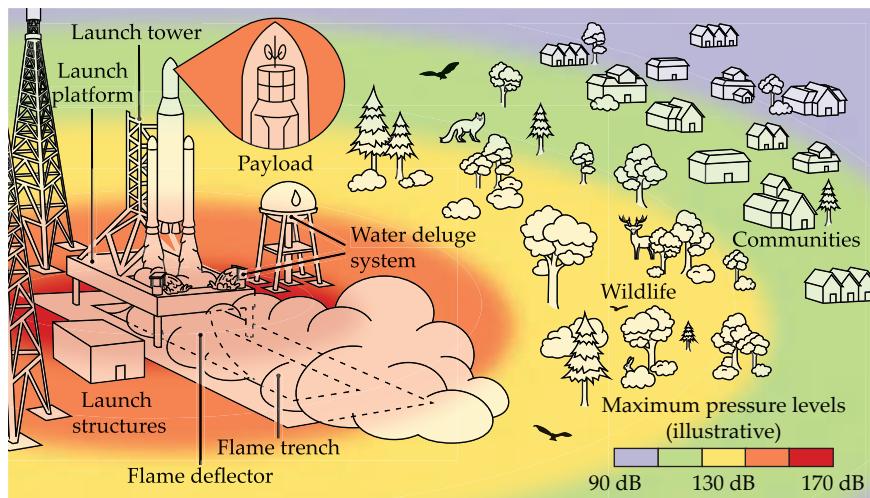
A decibel scale has no physical meaning until a zero point is defined. Without that reference a decibel value describes only relative changes, such as a 3 dB increase for a doubling of sound power. For sound, the 0 dB point is 1 pW; for pressure it is 20  $\mu$ Pa. Although a large rocket may generate a sound-power level in excess of 200 dB re 1 pW, maximum overall pressure levels near the rocket plume will be considerably less—somewhere around 170–175 dB re 20  $\mu$ Pa. Both represent extreme sound levels.

Rocket noise sources change during the startup and launch sequence. During engine startup, an ignition overpressure (IOP) often occurs. A supersonic plume of gas emerges from the rocket nozzle, rapidly heating and expanding the ambient air. The high-amplitude pressure transient can be particularly intense for solid-fuel boosters: The IOP peak-pressure level during the recent *Artemis 1* launch reached nearly 146 dB re 20  $\mu$ Pa—above the ear's pain threshold—at a distance of 1.8 km.

Turbulent mixing noise is then created as the plume, leaving the nozzle at velocities of 2500–4000 m/s, interacts with the ambient air to generate large-amplitude pressure fluctu-



**FIGURE 1. TURBULENT PLUMES** of exploding gas (left) emerge from the triple-core Delta IV Heavy rocket during the launch of the *Parker Solar Probe*. The pictured wavefronts (right) represent the changing sound-radiation wavelengths—from green (the shortest) to purple (the longest). Their directionality changes with the local velocity of the gas. Those different wavefronts and directionalities alter the received sound character at 1 km from the rocket during early-, peak-, and late-launch noise phases.



**FIGURE 2. TWENTY-FIVE HUNDRED TONS** of hardware and humans typically take off in a rocket launch. To reduce the heat and dissipate the sound, a million or more liters of water are normally released onto the launch pad in under a minute during liftoff. A flame trench below the pad deflects the plume of smoke and flames produced by the rocket boosters. Wildlife and neighbors within several kilometers experience high sound-pressure levels.

ations. That supersonic turbulence results in Mach waves—an efficient form of noise radiation whose directionality depends on the local turbulence velocity and ambient sound speed.

As figure 1 illustrates, Mach waves formed close to the nozzle originate from small-scale turbulence, resulting in short acoustic wavelengths and a broadband spectrum that has a relatively high peak frequency. The higher-frequency noise radiates at greater angles relative to the plume exhaust than the low frequencies, which are generated farther downstream from larger-scale turbulence with lower convective velocities. That low-frequency noise can persist for several minutes, late into the launch.

A frequency-dependent noise origin and directionality cause the noise spectrum's shape, peak frequency, and overall sound level to vary with angle. A person viewing a launch hears a clear downward shift in the pitch of the noise as the rocket lifts off, but that change is caused by the noise-generation physics rather than the Doppler effect. In addition to the IOP and Mach-wave radiation, our understanding of rocket noise is complicated by the plume's deflection from the flame trench—a deep concrete channel, shown in figure 2, covered by heat-resistant bricks—and by the rocket's acceleration.

It's not just the long-range sound levels that make observing a rocket launch impressive. The penetrating low-frequency roar and rumble are also accompanied by an intense crackling sound, frequently commented on at space shuttle launches and now generally associated with rockets and high-power military jet aircraft. The crackle is caused by shocks—near-discontinuous pressure jumps—in the noise waveform and result from nonlinear wave phenomena.

## Attenuating the noise

The rocket's noise intensity can create potentially destructive impacts. Figure 2 illustrates the launch-pad environment and the pressure levels experienced nearby. Vibrations from direct acoustic radiation and pad-reflected Mach waves—with overall levels exceeding 140 dB re 20  $\mu\text{Pa}$  inside the rocket payload fairing—can damage electronics, optics, and other sensitive equipment.

To protect the payload, rocket, and launch-pad structures, a huge volume of water is released from a tower nearby that

floods the launch platform during liftoff. The inundation typically reduces the noise by 3–5 dB (50–70%) by absorbing sound via bubbles and converting the acoustic energy into heat. Flame trenches also reduce the intensity of Mach and impingement waves that radiate energy back toward the rocket.

The noise also causes environmental and community concerns. Launch complexes often double as wildlife preserves for endangered species, and an increased launch cadence or construction of new spaceports can be worrying. Endangered birds, such as the western snowy plover and the California least tern, nest along beaches at Vandenberg Space Force Base. And NASA's Kennedy Space Center shares its borders with the Merritt Island National Wildlife Refuge, home to several endangered species.

Noise may startle birds or alter their vocalizations during mating and nesting seasons. In nearby communities, where levels may exceed 100 dB re 20  $\mu\text{Pa}$ , low frequencies transmit into homes and cause vibrations that rattle windows, damage historic structures, annoy homeowners, and ruin people's sleep. Collectively, there is a pressing need to better understand the noise-generation mechanisms, noise propagation, and the multitude of impacts of rocket-launch noise.

The world is entering an era with unprecedented need for access to space. Although researchers qualitatively understand some of the effects of rocket-noise physics and impacts, they still need to develop noise-emission models and metrics that better describe the unique sound characteristics and the associated community and environment effects. Sustained research is needed so scientists can accurately predict and mitigate those impacts—including vibroacoustic and environmental—to launch the new space age.

## Additional resources

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- K. L. Gee et al., "Saturn-V sound levels: A letter to the Redditor," *J. Acoust. Soc. Am.* **152**, 1068 (2022).
- K. L. Gee et al., "Space Launch System acoustics: Far-field noise measurements of the Artemis-I launch," *JASA Express Lett.* **3**, 023601 (2023).

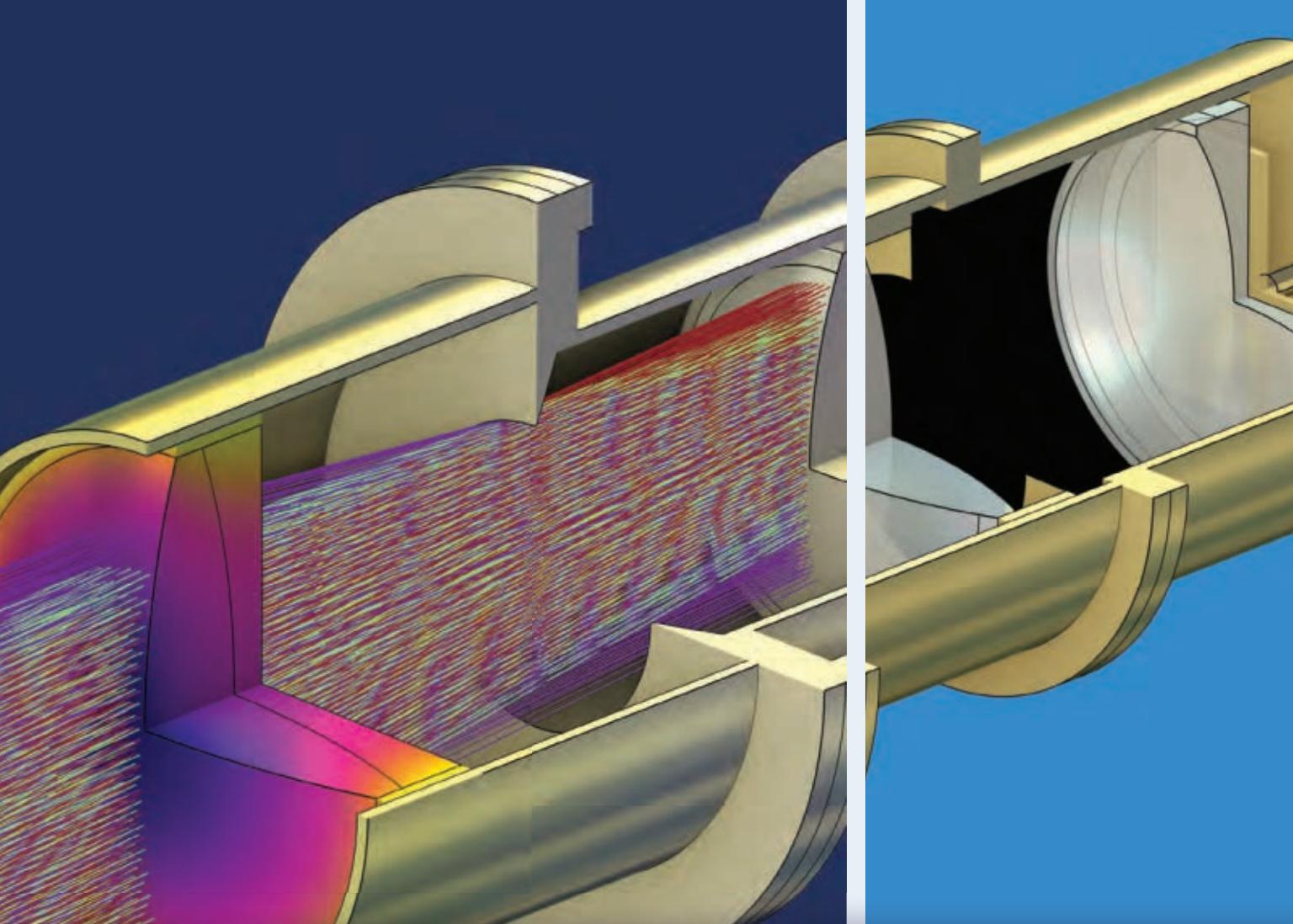
## Focusing with a spiral lens

The spiral-shaped pattern of the contact lens shown here allows the wearer to clearly see multiple objects at different distances. Progressive lenses and multifocal contacts also make it possible to focus on objects at various distances. But a wearer's peripheral vision may be reduced with progressive lenses, and multifocal contact lenses lose their focusing capabilities when the irises constrict. Spiral contacts avoid those problems, and they work well for different pupil diameters as lighting conditions change. The proof-of-concept lens, made by Bertrand Simon of the Institut d'Optique Graduate School in Paris-Saclay and colleagues, could find applications in eye care or be incorporated into miniaturized imaging systems.

The unique, free-form design of the spiral lens causes refracted light to twist like a corkscrew around the axis of travel. The result is that the individual light rays meet at multiple focal points, and objects at multiple distances are clearly defined. The researchers' initial simulations and measurements show that the spiral lens works just as well as a trifocal contact lens at smaller apertures—the holes through which light can pass—and better at larger apertures. (L. Galinier et al., *Optica* **11**, 238, 2024; image courtesy of Laurent Galinier.)

—AL

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