PHYSICS TODAY

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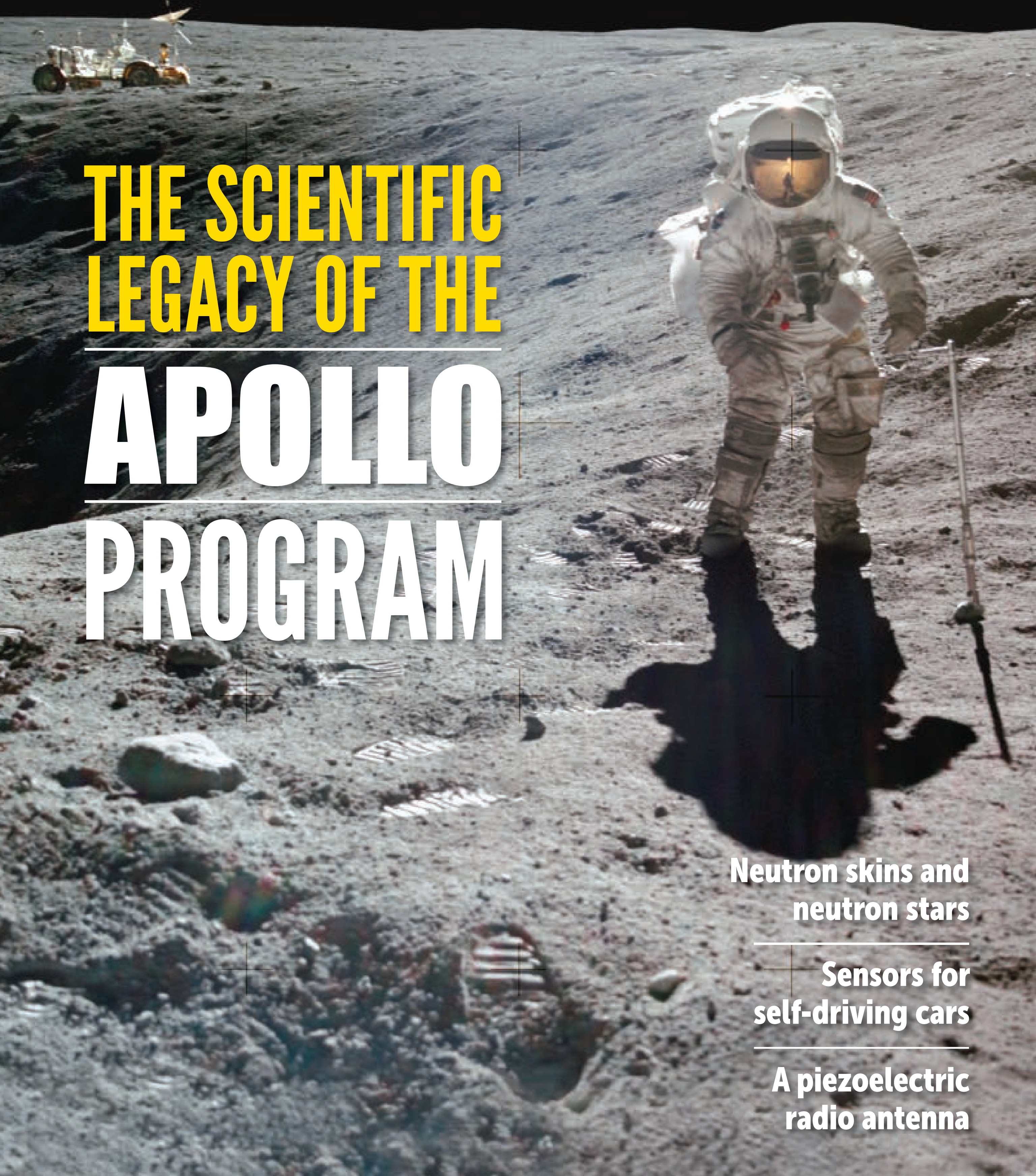

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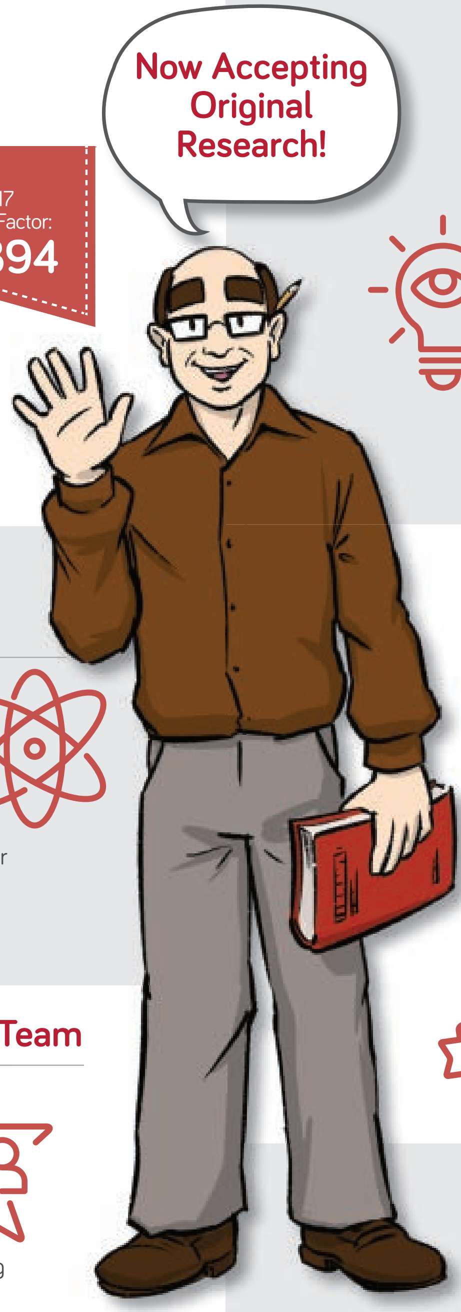

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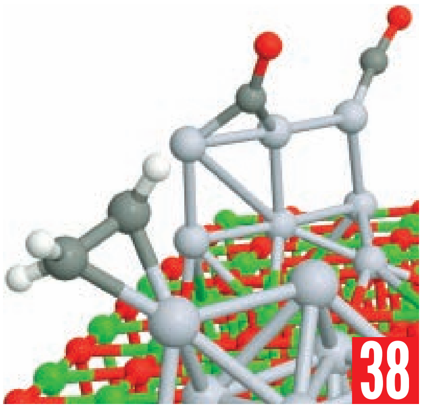
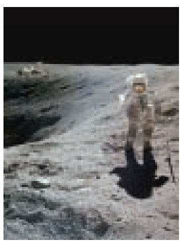
PHYSICS TODAY

July 2019 | volume 72 number 7

FEATURES

ON THE COVER: Astronaut Charles M. Duke Jr collects lunar samples next to the rim of Plum Crater during the first *Apollo 16* extravehicular activity on 21 April 1972. The parked lunar rover sits in the background. On **page 44**, Brad Jolliff and Mark Robinson discuss the achievements and scientific legacy of the Apollo program. (Photo taken by astronaut John W. Young. Courtesy of NASA.)

Recently on PHYSICS TODAY ONLINE

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TERRY THRELFALL

▶ Melt mystery

In 1896 chemist Emil Fischer produced a crystal that sometimes melts at 65 °C and sometimes at 100 °C. It took 123 years to learn how that could happen. David Adam explains how researchers determined that identical crystalline solids can melt into structurally distinct liquids.
physicstoday.org/Jul2019a

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▶ Serkan Golge

On 29 May physicist and dual US–Turkish citizen Serkan Golge was released from prison in Turkey after a nearly three-year incarceration on charges that the US government and human rights organizations called unsubstantiated. Golge talks to PHYSICS TODAY about his experience and his desire to return to physics research.
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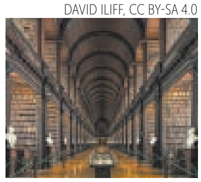

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▶ Plan S

If implemented, Plan S would require recipients of research grants from a dozen European national funding agencies to publish work in open-access journals. Dalmeet Singh Chawla details recently announced revisions to the controversial policy, including a delay in adoption until 2021.
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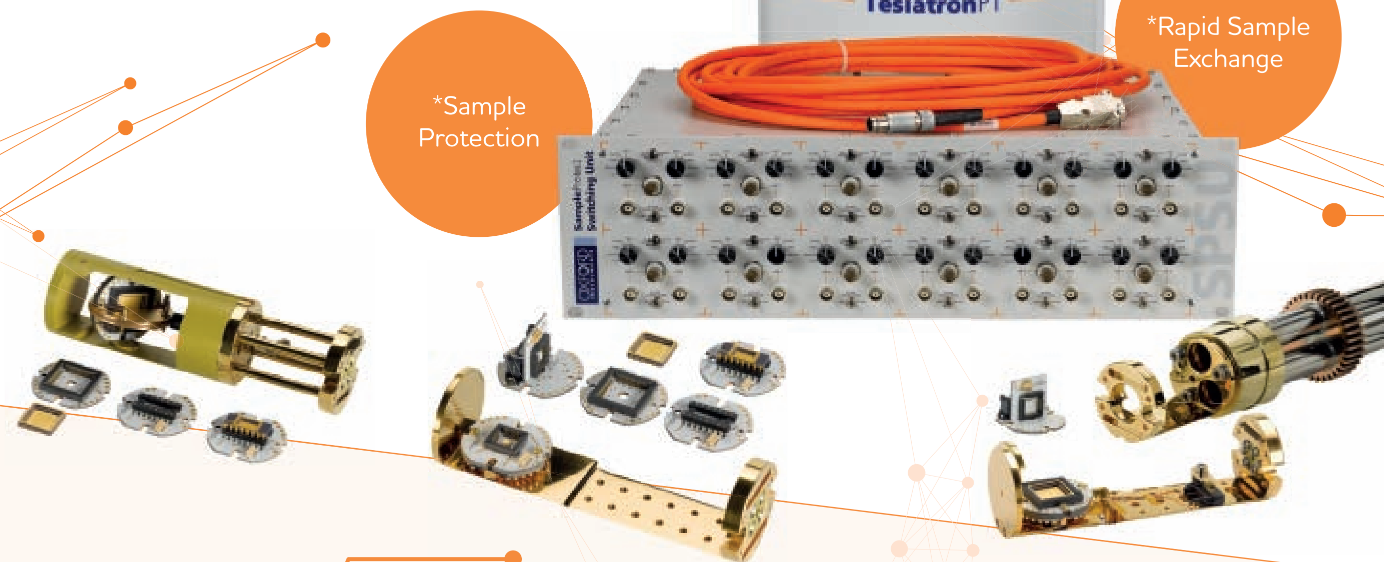

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Destination Moon

Charles Day

On 26 March the National Space Council met at the US Space and Rocket Center in Huntsville, Alabama. There, the council's chair, Vice President Mike Pence, announced the administration's new goal of returning American astronauts to the Moon by 2024. Seven weeks later the Trump administration added an extra $1.6 billion to its FY 2020 NASA budget request to fund the mission, which NASA has named Artemis after the twin sister of the Greek Sun god, Apollo. Far more funding will be needed in the next four annual budgets.

Five years is unlikely to be enough time. On 30 May the US Government Accountability Office (GAO) issued its 11th annual assessment of NASA's biggest projects. Three of them—the Space Launch System, the Orion Multi-Purpose Crew Vehicle, and Exploration Ground Systems—are essential to landing astronauts on the Moon. The GAO auditors found that, together, the systems are $1.8 billion over budget and 38 months late. NASA's average launch delay, at 13 months, was the longest the office had found since 2009, when it first started reviewing the space agency's performance.

Whereas the GAO is skeptical of NASA's ability to meet its own deadlines, Pence repeatedly stressed the need to revisit the Moon soon. "Urgency must be our watchword," he told his Huntsville audience. "Failure to achieve our goal to return an American astronaut to the Moon in the next five years is not an option." NASA, he said, had to become leaner, more accountable, and more agile.

Given what it will take to return astronauts to the Moon by 2024, it's worth examining just how urgent the goal really is. The scientific case is perhaps the easiest one to assess. In 2011 the National Research Council published its most recent decadal survey of planetary science. When the committee members evaluated scientific opportunities, returning astronauts to the Moon was not White House policy. Without the prospect of piggybacking on a manned mission, the Moon was considered a potential destination for robotic missions along with all the other bodies in our solar system.

The decadal survey made recommendations for two classes of missions, flagship and the smaller yet still ambitious New Frontiers. Retrieving samples from the surface of Mars was the highest priority among flagship missions, followed by visits to Jupiter's moon Europa and the planet Uranus.

Lunar science was the goal of one of five recommended candidates for the next New Frontiers mission: Specifically, retrieving samples from the ice-rich, deeply impacted Aitken basin at the Moon's south pole. The scientific payoff would be great. Indeed, the south pole is the intended destination of the 2024 Moon shot. But the next New Frontiers mission, to be announced later this month, will be either to Saturn's moon Titan or to comet 67P/Churyumov–Gerasimenko.

What of other, nonscientific cases to return astronauts to the Moon by 2024? To his credit, Pence did not equivocate. The US must remain first in space, he said, because the rules and values of space will be written by those who get there first and commit to staying. He's likely correct. In 1979 the United Nations Office for Outer Space Affairs promulgated a treaty to establish regulations for the use of the Moon and other celestial bodies and to grant the UN jurisdiction over them. Eighteen countries have acceded to or ratified the treaty; China, Russia, and the US are not among them. Mining oxygen from lunar rocks and using nuclear power to extract water from permanently shadowed craters—two activities that Pence mentioned in his Huntsville address—contravene Article 11 of the Moon Treaty, which forbids the appropriation of lunar resources by states and companies.

Who might reach the Moon before the US? On 28 November 2018, Dmitry Rogozin, head of Russia's national space agency, announced Russia's intention land a human on the Moon by 2030. Two years earlier, Zhang Yulin, the deputy commander of the China's manned space program, announced the country's intention to land a human on the Moon by 2036.

Does it matter if NASA goes all out to return to the Moon by 2024? Yes, I think it does. In its report, the GAO noted that the combination of NASA's existing overruns and the addition of Artemis will strain NASA's budget: "NASA will have to either increase its annual funding request or make tradeoffs between projects." Those tradeoffs could include the scientifically fruitful robotic missions that the decadal survey identified. I favor returning American astronauts to the Moon, just not at any cost. PT

TURN TO PAGE 22
FOR DAVID KRAMER'S
REPORT ON USING
THE MOON
AS A WAY STATION
TO MARS

READERS' FORUM

Commentary

The universe and the university: Physics preparation for academic leadership

No school or degree specifically prepares a person for becoming a university president, provost, dean, or other academic administrator. Institutions of higher learning instead seek people with demonstrated management talent in their specific disciplines and count on them to translate those skills to administration. The institutions often find that physicists have developed a powerful skill set for leadership.

My physics background equipped me for roles as dean, vice president, and president. I acquired the mind-set and skills to manage the major topics of concern in those positions: complexity management, data-driven decision making, design and long-range planning, communication, globalization, and diversity and inclusion. In academic administration, I depend every day on the lessons I learned in physics. Following are ways that a physicist's knowledge and skills can help in addressing the six topics of concern.

What physics taught me

▶ **Managing complexity.** A university is a very elaborate organization with widely diverse elements—faculty, students, staff, departments, curricula, laboratories, and so on. Physicists are taught to deal with extremely complex ideas and processes—as small as a subatomic particle or as big as the universe. I was drawn to physics by the interconnectedness of nature and the apparently simple laws that govern it. As my research career broadened, I studied ever more intricate systems—soft-matter materials, the underlying principles of thermodynamics, statistical physics, and often-unexpected responses to constraints, external forces, and stimuli. I explored how systems adapt, evolve, self-organize, and reveal complex patterns.

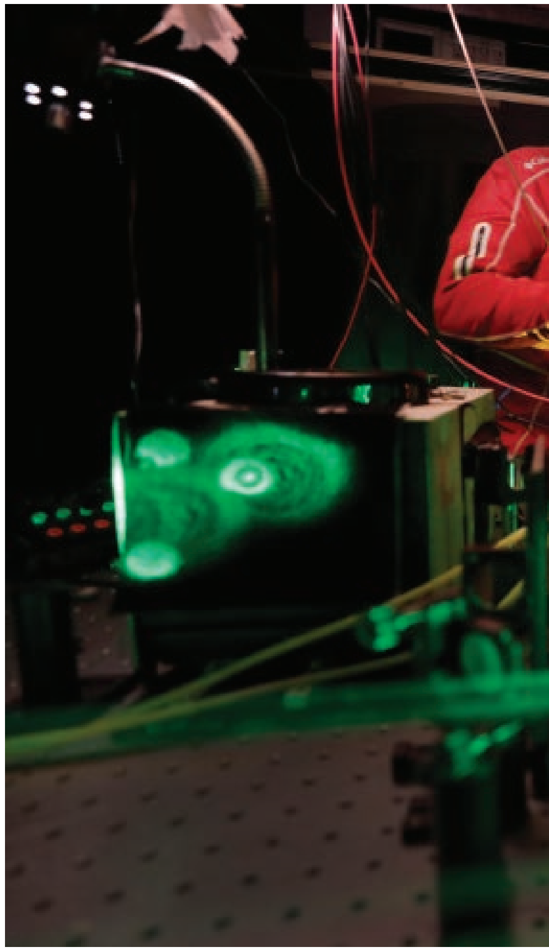
Academic leadership likewise involves both attention to detail and breadth of vision. A university community is organized, at least in theory, to align individual interests with the institution's vision. Fostering such a unifying vision for a complex organization is necessary for academic leadership today, and it is analogous to a physicist's understanding complex systems in nature.

▶ **Driving with data.** The accelerated dependence on data analytics in higher education means that quantitative skills are needed more than ever. Physicists are adept at comprehending data, identifying trends, and discovering patterns. From those data, they imagine things that have never been seen. They are equipped to recognize problematic data, misinterpretations, and hypotheses drawn from incorrect information. They must translate data into a story, starting with the question and narrating the path to the solution. Physicists tend to be great storytellers.

In academic oversight, much is driven by data, from devising financial models to leveraging artificial intelligence for student success. The capacity to analyze whether data are accurate and reliable and the skill to communicate the analysis with a compelling story are vital contributions physicists can bring to university administration.

▶ **Transcending barriers.** Today's global challenges are bigger than any single a cademic discipline can address. Universities need leaders who can break down silos and unite disparate expertise into powerful collaborations.

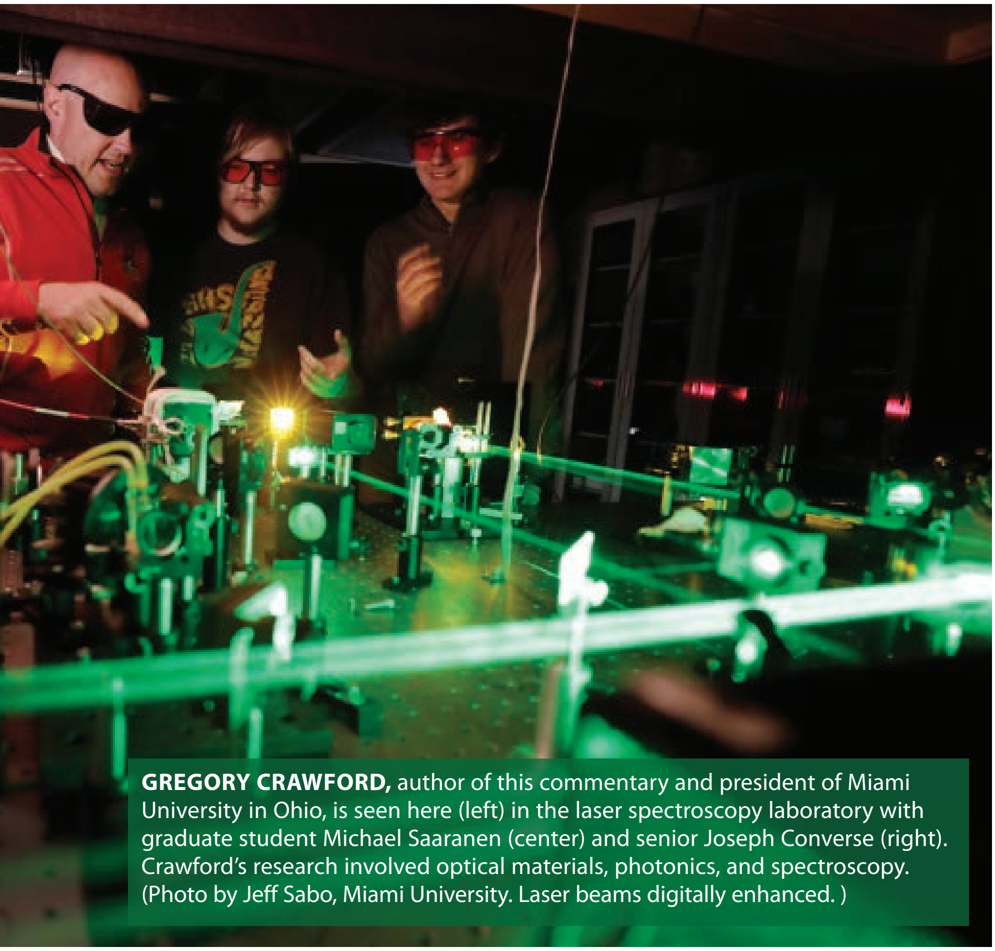
Physics touches many other disciplines, and it inspired me to be a perpetual student. My education first crossed boundaries from theoretical to computational to experimental physics, reached across different subdisciplines, and then



moved from pure to applied physics. Collaborations broadened; I worked with chemists and mathematicians, then with various engineers, and even with medical doctors. We reached the best solutions by presenting and discussing disagreements with humility and openness. My physics background enabled me to cross all those boundaries.

Universities by definition embrace a broad range of disciplines, departments, colleges, and programs. The capacity to unify faculty and staff across them all and forge a shared vision and mission is a skill that physicists can bring to higher education.

▶ **Designing with purpose.** In the fast-moving modern environment, universities can no longer expect to create and execute long-term plans without constant attention to unexpected events. To physicists, a "problem" is not an obstacle but a question not yet answered, and we tend to be confident in the progress made using the scientific method. I designed experiments that could fail or succeed or that could cause the research team to pivot when we saw an anomaly more ex-



GREGORY CRAWFORD, author of this commentary and president of Miami University in Ohio, is seen here (left) in the laser spectroscopy laboratory with graduate student Michael Saaranen (center) and senior Joseph Converse (right). Crawford's research involved optical materials, photonics, and spectroscopy. (Photo by Jeff Sabo, Miami University. Laser beams digitally enhanced.)

citing than we had imagined. Academic leadership requires that collaborative approach of ideation, prototyping, and testing. Physicists can offer that kind of organizational thinking and processing.

▶ **Communicating with integrity.** Universities must communicate with a wide range of stakeholders—faculty, students, staff, parents, external partners, and the public—with transparency and integrity. Likewise, physicists must communicate their work to both their peers and the public in a clear and honest way. An important root of my approach is educational outreach; I started as a graduate student who taught modern physics to middle school students. That work trained me to make esoteric ideas exciting and accessible. As a professor, I learned to adjust the content level from middle schoolers to doctoral candidates. I might explain my research to young students in the morning and to my physicist peers at an afternoon conference. The balance instilled in me a capacity for clarity and the humility to accept criticism.

▶ **Engaging diversity.** Universities should be at the forefront of promoting diversity and inclusion, responding to the shifting demographics of society, and preparing students for the real world. Physics as an objective science naturally transcends national, ethnic, cultural, racial, religious, and other divisions. My global experience suggests that physicists all share a common language. In academic leadership, the common language is the mission, purpose, and core values that can unite people from all kinds of backgrounds. Physicists can bring such an inclusive mind-set.

What physics didn't teach me

Just as I constantly adjusted my approach as a physicist, my transition to academic stewardship required new learning. Some necessary undergraduate work, especially in liberal arts, complemented the rigorous quantitative side of my education. Those fresh perspectives made me a better physicist. For example, the objective nature of physics can obscure the fact that science is a human endeavor. Character matters in research, reporting, and interpersonal relationships. Physicists should ask not only can we do this but should we, and the best of them give attention to effects on human well-being. So should academic administrators. Moreover, academic leadership requires living with ambiguity, acting on incomplete data, and practicing negotiation in a way that physics typically does not. If you are a physicist interested in making this career change, consider the following areas:

▶ **Accepting ambiguity.** As a physicist, my work is unfinished until I have a clear, compelling, evidence-based result that makes a reliable contribution to the field. Until then, I must conduct more experiments to test my hypothesis or fill evidentiary gaps.

Unlike physics, academic administration involves such variables as human choice, intellect, emotion, and interpersonal and social issues. Universities are more complex than the physical world of action–reaction relationships; no fixed, natural laws govern the social, economic, and political environment. We must engage that world with wisdom, flexibility, and courage to adapt based on our best understanding of a given situation. That is a central feature of modern academic leadership.

▶ **Acting boldly.** Unlike physicists, who must have all the necessary data before they can publish or present results, academic leaders often must act on incomplete information, live with the consequences, and be able to pivot as circumstances require. Academic leaders must lead with confidence and courage in a rapidly evolving environment.

▶ **Building consensus.** Physicists build consensus through empirical evidence. Data are not subject to negotiation, and scientific conclusions are not reached through compromise. Academic leaders, however, must consider multiple perspectives and proposals. Higher education, like society, progresses not by discovering the hidden secrets of the universe but by engaging, respecting, and enlisting people to work toward success for all. Leading such a group requires personal qualities that inspire dedication and unity.

Individuals reach the top levels of academic leadership through multiple disciplinary paths, each providing a particular combination of knowledge, skills, mind-sets, and experiences. After a decade at three top-tier universities, I know my physics background equipped me for the administrative work I'm doing. I believe higher education will flourish as more professionals from physics bring their talents to serve as leaders. The dynamic and quantitative focus in those roles makes me grateful for the preparation I received in physics.

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LETTERS

Reflections from gems in the old literature

A graduate school adviser, Christopher Shera, recently brought to my attention Ray Goldstein's article "Coffee stains, cell receptors, and time crystals: Lessons from the old literature" (PHYSICS TODAY, September 2018, page 32). The author, as it happens, was a key undergraduate mentor to me. I recall, during a summer at the Santa Fe Institute, helping Professor Goldstein set up a loudspeaker with a water-filled petri dish on top to produce Faraday instability patterns such as those shown in the article's figure 3b. Even more remarkable was the article's figure 1, which reminded me of making a movie of coffee-ring formation for Greg Huber in the summer of 2000. The video aired that evening on the nightly news in connection with a now highly cited paper.[1]

The main thread of Goldstein's article—the joy and value of reading "widely"—is important and deserves voicing. The task gets harder daily as the body of scientific literature keeps growing at an extraordinary rate. The article reminded me, an auditory scientist, of a once-forgotten 1948 paper by Thomas Gold that suggested the notion of an "active ear."[2] David Kemp's discovery of otoacoustic emissions 30 years later[3] reignited the idea, and it now lies at the foundation of modern cochlear mechanics. Gold's paper is acknowledged, cited, and widely celebrated.

My recollection of that paper reminded me of a quote by Werner Heisenberg: "What we observe is not nature in itself but nature exposed to our method of questioning." Beyond Goldstein's narrative, I'd suggest that seeing a wider context for the convoluted and technical details of our field is crucial. Making the broad connections helps us enormously.

Consider diffusion, a central heuristic in Goldstein's narrative. I like to pose simple yet intuitive scientific questions for my students. For example, How does one's brain work? The short answer is that we don't really know. The longer and better answer is that we have many of what we believe are essential bits and pieces, such as spiking neurons, excitatory and inhibitory interactions, and network plasticity. And at the core of those are key concepts learned in freshman physics: oscillations, electric potentials, capacitance, and others.

Diffusion, though, is only rarely found in first-year physics materials, yet it is essential to spiking neurons. Electrodiffusion lies at the heart of the Hodgkin–Huxley model, which was laid out in a classic set of papers.[4] It also is vital to interneuron communication and plastic changes such as connection weights in Hebbian theory. Although the role of diffusion is central to many of Goldstein's scientific examples, it is also important in everyday phenomena, which include the sensory and neural processes involved in reading this letter. Incidentally, diffusion can serve as a wonderful pedagogical means to introduce undergraduates to more sophisticated concepts—for example, multivariable functions, differential equations, probability, and bridging micro- and macroscopic domains.

Budding scientists may hear the term "diffusion," hit that Google Search button, and immediately find themselves at a Wikipedia page. A somewhat useful general resource, it is unlikely to have any clear indications that diffusion is "a

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process foundational to how your brain works." No, you need the "serendipitous kind of rediscovery" Goldstein mentions to find such connections yourself. That continual process of renewal is what keeps us going when we hit those inevitable dead ends. And the combination of reading widely and making broad connections is a fruitful form of renewal. (See, for example, Douglas Hofstadter's 1979 classic *Gödel, Escher, Bach: An Eternal Golden Braid*.)

References

1. R. D. Deegan et al., *Phys. Rev. E* **62**, 756 (2000).
2. T. Gold, *Proc. R. Soc. B* **135**, 492 (1948).
3. D. T. Kemp, *J. Acoust. Soc. Am.* **64**, 1386 (1978).
4. See A. L. Hodgkin, A. F. Huxley, *J. Physiol.* **117**, 500 (1952) and references therein.

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One of the papers chosen by Ray Goldstein in his survey of gems in the old literature (PHYSICS TODAY, September 2018, page 32) is by Theodor Engelmann, who used oxygen-sensitive putrefying bacteria to determine the wavelength dependence of photosynthesis. Engelmann (1843–1909) made important contributions to physiology, botany, and photosynthesis; less well known is that he was an excellent cellist and a close friend of Johannes Brahms, who dedicated his String Quartet no. 3 to him. Engelmann, in turn, sent Brahms his scientific papers. When in Utrecht, the Netherlands, Brahms often stayed with Engelmann and his wife Emma, herself an eminent pianist, and played chamber music with them.

Known for the brevity and haste of his correspondence, Brahms wrote an unusually long, light-hearted, rambling letter to Emma after he received her husband's papers. In his letter, Brahms whimsically links the dissolved O (oxygen) that attracts the bacteria (aerotaxis) to the ohs and ahs that art evokes in sensitive persons and he wonders what music would be without these. Styra Avins included and discussed the letter in *Johannes Brahms: Life and Letters* (1997; letter number 403).

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Bhabha's legacy: Atoms for peace and war

The article by Stuart Leslie and Indira Chowdhury on Homi Bhabha's many accomplishments to advance science and technology in India (PHYSICS TODAY, September 2018, page 48) made only a few oblique references to that country's nuclear weapons program. India's speed in achieving the successful detonation of a 12-kiloton device in 1974 was clearly due to the infrastructure that Bhabha initiated and guided.

Although the explosion, carried out by the Indian Army, was termed "Smiling Buddha," then prime minister Indira Gandhi called it a "peaceful test." Nonetheless, it initiated a nuclear arms race with Pakistan (see Stuart Leslie's article "Pakistan's nuclear Taj Mahal," PHYSICS TODAY, February 2015, page 40). Thus Bhabha could be called the father of Indian nuclear weaponry. One wonders whether nuclear weapons development was his main justification for establishing the Trombay complex.

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▶ **Leslie and Chowdhury reply:** Homi Bhabha clearly designed Trombay with nuclear weapons as more than an afterthought, though Bhabha himself remained ambivalent about a nuclear-armed India. The CIRUS heavy-water reactor and its successors produced weapons-grade plutonium that supplied the material for India's first atomic bomb, and the plutonium itself was extracted in the facility designed by Edward Durell Stone for the Trombay campus. In India—as in France, Israel, and every other member of the nuclear fraternity—atoms for peace could never be entirely separated from atoms for war.

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Dark-matter detector observes a rare nuclear decay

The result shows that the exquisitely sensitive apparatus's potential extends beyond the purpose for which it was built.

Dark matter must exist. Gravitational phenomena such as the rotation of galaxies (see PHYSICS TODAY, December 2006, page 8) and lensing of light from distant stars (see PHYSICS TODAY, June 2015, page 18) consistently show signs of far more mass than ordinary protons, neutrons, and electrons can account for. Unless there's some large but subtle gap in the theory of general relativity, the universe must be swarming with some mysterious particles that feel the force of gravity but can't be seen or touched.

What those particles are is anyone's guess. One possibility—that dark matter is made of weakly interacting massive particles, or WIMPs—is appealing because it arises theoretically out of solutions to unrelated problems in particle physics. WIMPs, if they exist, could interact with ordinary matter not just gravitationally but also via a force on the scale of the weak interaction that neutrinos experience. So in principle, they can be detected the same way neutrinos are: Gather a large quantity of some material that's expected to produce a distinct scattering signature, put it deep underground to shield it from cosmic rays, surround it with sensors, and wait.

Dozens of would-be WIMP detectors have been built and operated over the years in underground labs around the world. With the exception of disputed results from one group (see PHYSICS TODAY, July 2016, page 28), they've all come up empty so far. But even if WIMPs aren't the solution to the dark-matter puzzle, the effort to observe them needn't be all for naught. The extraordinarily sensitive detectors, painstakingly rid of almost all background, are in a position to make measurements that no other experiments can, and they potentially can uncover new physics in quarters unrelated to dark matter.

FIGURE 1. THE XENON1T DETECTOR before it was installed in 2016. The cylindrical vessel, roughly 1 m across and 1 m high, contained 3.2 tons of mostly liquid xenon at an operating temperature of −96 °C. The top and bottom faces were lined with photomultiplier tubes to detect and measure the energies of scattering events and radioactive decays. (Courtesy of the XENON collaboration.)

The XENON collaboration, founded in 2002 by Elena Aprile of Columbia University, has just made that potential look a lot more like a reality.[1] With its detector—which unsurprisingly uses chilled xenon as its target material—at Gran Sasso National Laboratory in Italy, the group has observed a rare form of nuclear decay, two-neutrino double-electron capture (2νECEC), in the neutron-poor isotope ^{124}Xe.

The result itself is not terribly startling. Nuclear theory predicts that ^{124}Xe should undergo 2νECEC, and the measured half-life is in line with expectations. But it's an experimental tour de force. Less than 0.1% of natural Xe is ^{124}Xe, and its half-life, $(1.8 \pm 0.6) \times 10^{22}$ yr, is the longest ever measured directly. As WIMP detectors continue to improve, they'll be ready to observe even rarer events. One much-discussed possibility is the neutrinoless version of the same decay, 0νECEC. If detected, 0νECEC would establish that neutrinos are their own antiparticles and that lepton number is not conserved.

Slow decay

A cousin of two-neutrino double-beta decay ($2\nu\beta\beta$; see PHYSICS TODAY, December 1987, page 19), 2νECEC is also related to single-beta decay and single-electron capture. All are based on the same fundamental weak interaction: Either a neutron decays into a proton, an electron, and an antineutrino, or a proton and electron combine to yield a neutron and a neutrino. (Nuclear-physics parlance isn't always fussy about distinguishing neutrinos and antineutrinos, but to conserve lepton number, they need to be counted as different particles.)

Nuclides that undergo beta decay include tritium and carbon-14, with half-lives of 12 yr and 5700 yr, respectively. But $2\nu\beta\beta$, which requires the weak process to happen twice simultaneously, is correspondingly more infrequent: All known half-lives are greater than 10^{18} yr, so it's detectable only in nuclides for which single-beta decay is forbidden or strongly suppressed.

In general, 2νECEC is rarer still, be-

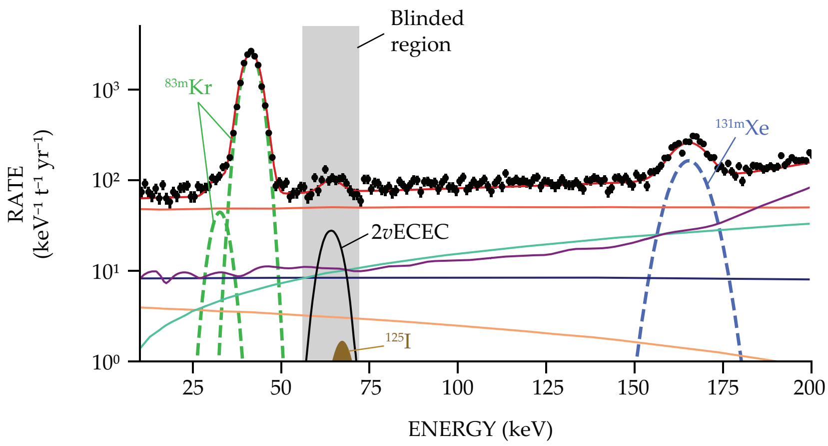

FIGURE 2. THE ENERGY SPECTRUM from nearly half a year's worth of XENON1T data. The two-neutrino double-electron capture signal (2*ν*ECEC) appears as the small bump in the blinded region and is fitted by the black curve. The large green and blue peaks arise from metastable krypton and xenon nuclides used to calibrate the energy scale. All other curves represent sources of background; in particular, the small brown bump shows the expected contribution of the creation and decay of iodine-125. If the target Xe hadn't been constantly purified to remove all iodine, that peak would be much larger. (Adapted from ref. 1.)

cause it requires not just two simultaneous weak events but also two electrons to be localized in the nucleus at the same time. Before XENON's results, indications of 2*ν*ECEC had been directly observed[2] in only one nuclide, krypton-78, with a half-life of around 10^{22} yr. The decay mode is also known to occur in barium-130, with a half-life on the order of 10^{21} yr, but that was determined by analyzing geological samples for ^{130}Ba and its daughter nuclide ^{130}Xe, not by catching the atoms decaying in real time.[3]

Many other nuclides are expected to undergo 2*ν*ECEC, but they haven't been subjected to observation. It's just too costly and challenging to amass enough of the isotope of interest, build a detector capable of sensing the decays, and suppress background to the point where ultrarare events become visible. But Xe-based dark-matter detectors were doing all those things anyway. As a by-product of the hunt for WIMPs, they got a 2*ν*ECEC measurement essentially for free.

Multipurpose detectors

Efforts to use Xe-based WIMP detectors to look for 2*ν*ECEC began almost a decade ago with the XMASS collaboration, whose experiment is based at the Kamioka Observatory in Japan. Because the electrons captured in 2*ν*ECEC are almost certainly the core electrons of ^{124}Xe, the daughter atom, tellurium-124, is left in a highly excited state. As it relaxes, it produces a cascade of photons and electrons with a total detectable energy of 64 keV. The energetic particles cause the Xe to scintillate, and the emitted light is detected by photomultiplier tubes.

When the XMASS researchers looked for a peak in their energy spectrum at 64 keV, they found none.[4] They concluded that at the 90% confidence level, the decay should have a half-life longer than 2.1×10^{22} yr; otherwise, they would have observed it.

XENON also went through the motions of looking for the decay.[5] "But the experiment had no chance, since XMASS was more sensitive at that stage," says XENON team member Alexander Fieguth of Stanford University, who worked on the project while a student at the University of Münster. At the time, XENON was using its XENON100 detector with just 165 kg of Xe, and the XMASS detector had 832 kg.

It's typical for dark-matter groups to upgrade their detectors every few years, as they learn to overcome experimental challenges and gain more funding to buy more target material. In 2016 XENON unveiled its new XENON1T detector (shown in figure 1) with an immense 3.2 tons of Xe. But the increased mass contributed only part of the sensitivity improvement. Says XENON researcher Christian Wittweg, also a Münster student, "We screened each part of the detector—each screw, each photosensor, each cable—for tiny traces of radioactivity that cause backgrounds, and we selected only the lowest-radioactivity materials to build the detector."

From the start, the XENON researchers were prepared to look for 2*ν*ECEC. So they wouldn't be biased by their perception of the results, they kept the data between 56 keV and 72 keV hidden, or blinded, until the data taking and background characterization were complete. And they took measures to combat an especially pesky source of background: When ^{124}Xe captures a neutron, it transforms into ^{125}Xe, then iodine-125, then an excited state of ^{125}Te, which emits a signal at 67 keV that's easily mistaken for the 2*ν*ECEC signal at 64 keV. They can't prevent that sequence of reactions, but they can stop it in its tracks: The half-life of ^{125}I is 59 days, and they can purify their detector of all iodine much faster than that.

The results, based on 177.7 days of data from 2017 and 2018, are shown in figure 2. The green and blue peaks at either end are from metastable Xe and Kr nuclides created on purpose to help calibrate the energy scale. The solid brown peak shows what's expected to be left of the ^{125}I background: 10 or so events over the whole data set. And the small bump in the blinded region of the data is the 2*ν*ECEC signal.

It may not look like much—a few hundred events, barely visible above the already low background—but it's larger than the researchers expected. The corresponding half-life, $(1.8 \pm 0.6) \times 10^{22}$ yr, falls in the region XMASS had excluded with 90% confidence (although the error bars extend above the XMASS lower bound). "Nature was kind to us in providing such a large signal," says Fieguth. "It could easily have been a few times weaker, but it couldn't have been much stronger than what we saw."

The new generation

Detecting $2\nu\beta\beta$ is seen as a natural first step in looking for $0\nu\beta\beta$ (see PHYSICS TODAY, January 2010, page 20), and 2*ν*ECEC is no different. "Certainly, if we hadn't seen it, it would be a lot less feasible to look for an even more exotic decay," says Wittweg. The neutrinoless decays might not even be possible—neutrinos might not be their own antiparticles after all. But if they are, it would signal a major deviation from the standard model of particle physics that could unlock a host of new insights, including the secrets of the neutrino masses.

Because neutrinos can change flavor—an electron neutrino might turn into a muon neutrino or a tau neutrino, say—they must have three mass states that aren't the same as the three flavor states. The three masses are all different, so at least two of them must be nonzero, but it's not even known which one is the largest. In the so-called normal hierarchy—in which m_3, the mass of the state made up mostly of the muon and tau flavor states, is largest—the half-lives of neutrinoless decays would be roughly 10^{29} yr. In the inverted hierarchy, in which m_3 is the smallest, they're around 10^{27} yr. They're both far beyond the reach of current Xe-based detectors but could be observable by future ones.

As WIMP experiments become more sensitive, they could also double as real-time neutrino detectors in a uniquely low-energy regime. Right now, neutrinos from the Sun are just one of several sources of background—they appear as the orange curve in figure 2—but that can change as the detectors grow and other background components are comparatively reduced. Whereas water-based neutrino detectors, such as Super-Kamiokande, can see only those rare solar neutrinos produced by beta decay of boron-8 (see PHYSICS TODAY, December 2015, page 16), a Xe-based detector could provide a complementary view by detecting the far more numerous neutrinos from proton–proton fusion.

The XENON1T detector has already been shut down, and the XENON researchers are getting ready for their next upgrade, XENONnT, with 8 tons of Xe. It will be joined in the next few years by two other new detectors: LZ (for LUX–Zeplin, a merging of the Large Underground Xenon and the Zoned Proportional Scintillation in Liquid Noble Gases experiments) in South Dakota and PandaX-4T (Particle and Astrophysical Xenon detector) in Sichuan, China. The main goal is still to look for WIMPs, but it's now clear that that's not all the detectors are capable of. "Maybe we'll stumble upon something totally unexpected along the way," says Wittweg, "as so often happens in physics."

Johanna Miller

References

1. XENON collaboration, *Nature* **568**, 532 (2019).
2. Y. M. Gavrilyuk et al., *Phys. Rev. C* **87**, 035501 (2013); S. S. Ratkevich et al., *Phys. Rev. C* **96**, 065502 (2017).
3. A. P. Meshik et al., *Phys. Rev. C* **64**, 035205 (2001); M. Pujol et al., *Geochim. Cosmochim. Acta* **73**, 6834 (2009).
4. XMASS collaboration, *Prog. Theor. Exp. Phys.* **2018**(5), 053D03 (2018).
5. E. Aprile et al. (XENON collaboration), *Phys. Rev. C* **95**, 024605 (2017).

A raft of soap bubbles remembers its past

Information can be encoded in, and extracted from, the ostensibly random arrangement of a soft glass.

Amorphous materials, such as glasses and gels, are characterized by a plethora of available configurations that look much the same. With a single low-energy ordered configuration off limits—either because it doesn't exist or because it's kinetically inaccessible—their energy landscapes are rugged labyrinths with many local minima, each corresponding to a specific disordered arrangement of the constituent particles.

That disorder can carry more information than meets the eye. Amorphous solids are eternally out of equilibrium, and a hallmark of nonequilibrium thermodynamics is that systems retain information about their history. (For more about how that history dependence is exploited in glass physics, see the article by Ludovic Berthier and Mark Ediger, PHYSICS TODAY, January 2016, page 40.) Put another way, two configurations that are virtually identical in their bulk properties (such as density and energy) and microscopic measures (such as autocorrelation functions) are nevertheless distinct states, and they may be distinguishable by properties we don't yet know how to measure.

Now Srimayee Mukherji, her master's thesis adviser Rajesh Ganapathy, and their colleagues Ajay Sood and Neelima Kandula at the Jawaharlal Nehru Centre for Advanced Scientific Research in Bangalore, India, have shown experimentally[1] that they can manipulate the information contained in a raft of soap bubbles like the one shown in figure 1.

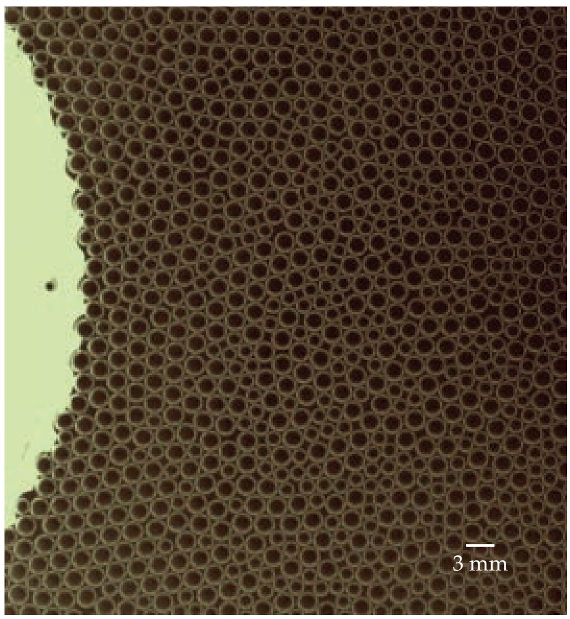

FIGURE 1. A BUBBLE RAFT in a Couette cell. Although the disordered arrangement of bubbles appears random, it contains information about shearing amplitudes the raft has experienced. (Courtesy of Rajesh Ganapathy.)

The bubbles' size distribution is chosen so that they can't settle into a configuration of crystalline order, and the system behaves like a soft glass. The researchers "train" the raft by applying shear oscillations at a particular strain amplitude γ_t. Shearing rearranges the bubbles in a way that seems to be random: No visible feature distinguishes a trained raft from an untrained one. Nevertheless, a suitable readout protocol can extract the value of γ_t several minutes or more after training. A single raft can even hold simultaneous memories of two different γ_t values—and in principle, more than that.

The memory appears to be related to the bubble raft's yielding transition. Below a shear strain $\gamma_y = 0.06$, the raft behaves like an elastic solid; for larger strains, it deforms plastically. Surprisingly, the system can remember γ_t values both greater and less than γ_y, and the closer γ_t is to γ_y, the stronger the memory signature. Although yielding behav-

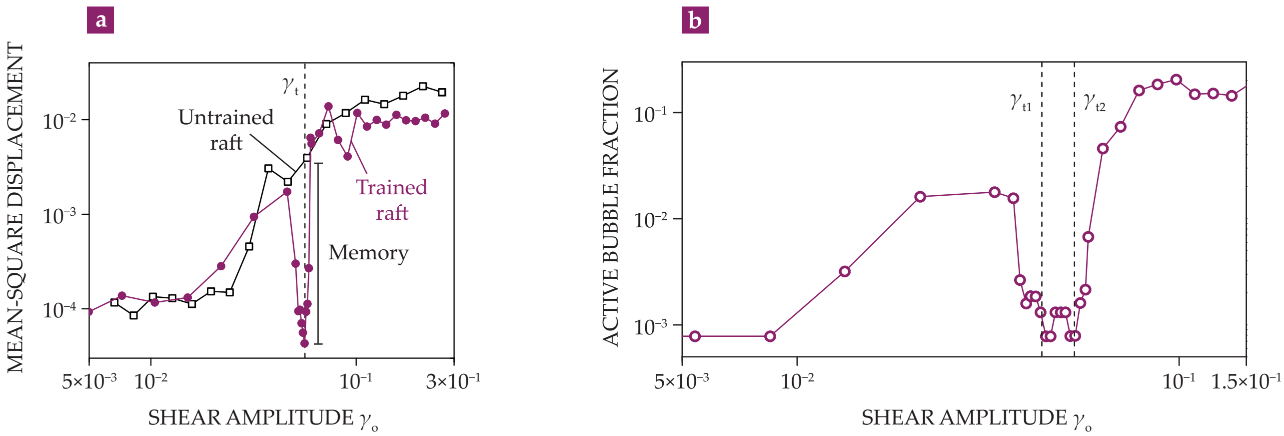

FIGURE 2. SIGNATURES OF MEMORY in a bubble raft's response to an increasing shear strain amplitude γ_o. **(a)** When a raft is trained by shear oscillations at $\gamma_t = 0.056$, its response (purple) looks much like that of an untrained raft (black) except for a sharp drop at γ_t. **(b)** A raft trained at two amplitudes, $\gamma_{t1} = 0.042$ and $\gamma_{t2} = 0.053$, remembers them both. (Adapted from ref. 1.)

ior is found in many everyday materials, including whipped cream and solid cooking fats (see the Quick Study by Braulio Macias Rodriguez and Alejandro Marangoni, PHYSICS TODAY, January 2018, page 70), a rigorous theory of the transition is still elusive.[2] The connection between memory and yielding has the potential to shed new light on both.

Raft training

Many condensed-matter systems exhibit memory of past conditions. In addition to all the systems used and explored for practical data storage, material memories include any system that exhibits hysteresis or is sensitive to its preparation pathway. Recent years have seen a push for a more unified view of memory phenomena, to draw connections among the behaviors of disparate systems.[3] For example, dilute colloidal suspensions under cyclic shear can remember their history in a way that bears a striking resemblance to how charge-density-wave solids remember the durations of electrical pulses (for an overview of the latter, see the article by Robert Thorne, PHYSICS TODAY, May 1996, page 42).

Five years ago, at about the same time as the experiments on sheared suspensions, a trio of theorists predicted a similar yet distinct memory behavior in sheared amorphous solids.[4] Ganapathy and his group, who had experience working with granular and colloidal systems under shear, decided to take a look. They opted to use bubble rafts rather than a system of solid particles, because the bubbles interact frictionlessly. The challenge was keeping the bubbles from bursting or coalescing during the experiment.

It's been known for a century that soap bubbles made by the right recipe can be kept stable for hours or longer; James Dewar, among his other achievements, was a pioneer of soap film research (see the article by Robert Soulen, PHYSICS TODAY, March 1996, page 32). But the bubbles in that early work weren't subjected to constant shearing and squeezing. Says Ganapathy, "We tried a whole bunch of different surfactants before we converged on one that worked"—a mixture of toy bubble solution and sodium stearate bar soap.

The bubbles are placed in a Couette cell, the 4-cm-wide annular region between an inner disk (visible at the left of figure 1) and an outer ring (not shown). Rotating the disk alternately clockwise and counterclockwise applies an oscillating shear strain whose amplitude the raft remembers. A typical training protocol comprises 17 oscillations with period 10 seconds.

The researchers characterized the response to shear oscillations by filming the raft and calculating how far each bubble moved from the beginning of one cycle to the beginning of the next. For training amplitudes γ_t much less than γ_y, the mean-square bubble displacement was always essentially zero: The raft deformed elastically, and each bubble returned to its original position. For larger values of γ_t, but still less than γ_y, the first few shear cycles rearranged some bubbles, but after that, the raft settled into a state of purely elastic deformation. For $\gamma_t > \gamma_y$, the mean-square displacement started high and decreased but plateaued at a nonzero value: No matter how much the raft is trained in the plastic regime, each new cycle always rearranges some bubbles.

In the readout protocol, the researchers applied a series of shear oscillations of gradually increasing amplitude γ_o, and they measured the raft response in terms of either the mean-square displacement or the fraction of bubbles displaced by more than a tenth of their diameters. Attempting to read an untrained raft (black data in figure 2a) shows nothing out of the ordinary: The deformation starts out elastic at low amplitudes and becomes gradually more plastic as γ_o is increased.

The readout of a trained raft (purple data in figure 2a) looks similar, except at γ_t, where the mean-square displacement drops by up to two orders of magnitude. Figure 2b shows the readout of a raft trained on two amplitudes, γ_{t1} and γ_{t2}; it simultaneously remembers them both. For each raft, to better measure the sharpness of the memory signals, the researchers scanned γ_o more slowly in the vicinity of the known training amplitudes. But the memory doesn't depend on that aspect of the readout protocol—they could just as easily have scanned γ_o at a constant rate to detect an unknown γ_t.

Curiously, trained rafts behave like untrained rafts even for $\gamma_o < \gamma_t$ (or γ_{t1} for the two-memory raft). That means not only that training at γ_t has no effect on the raft response at $\gamma_o < \gamma_t$, but that shearing at $\gamma_o < \gamma_t$—which rearranges some of the bubbles—doesn't disrupt the memory of γ_t. Both of those features remain to be fully understood.

Cryptic memory

"We expected to see memory in this system," says Ganapathy. "But personally, I expected to see a clear memory signature only beyond the yield point, because that is where the system has been reconfigured enough to be subsequently read out." In fact, the memory works equally well for γ_t just above and just below γ_y: All three of the memory signatures shown in figure 2 are for strains less than γ_y. On the other hand, the memory works poorly for values far from γ_y in either direction.

That unexpected behavior offers a new path to exploring the nature of the yielding transition itself. Deforming a material at or above the yield strain doesn't make all of it yield uniformly; some parts flow freely while others remain rigid. Previous experiments from Ganapathy's group[5] showed that at γ_y, spatial correlations between the flowing and rigid regions are maximized, and the system's relaxation time diverges, just like at the critical point of a second-order phase transition. And recent simulations have shown that shearing a model glass at γ_y helps it find its way into an ultrastable, low-energy (but still disordered) configuration.[6]

There's something about γ_y, it seems, that efficiently rearranges particles and explores the space of possible configurations. What that has to do with memory depends on where and how the memory is stored in the system. If, for example, memory of each γ_t value is encoded at a particular length scale, that could help explain how the system can remember multiple γ_t values at the same time and why shearing at γ_y, which accesses all length scales, strengthens the memory signature.

But that's all speculation for now, because it's still not clear what makes a trained raft structurally different from an untrained one. So far, the only known way to tell them apart is by performing the readout protocol. Despite their best efforts, the researchers haven't found a way to tell the two apart based on the positions of the bubbles alone. An audience member at one of Ganapathy's talks once asked if the effect might somehow be exploited in cryptography. "I don't know the answer," he says, "but there might be advantages to this form of memory."

Johanna Miller

References

1. S. Mukherji et al., *Phys. Rev. Lett.* **122**, 158001 (2019).
2. D. Bonn et al., *Rev. Mod. Phys.* **89**, 035005 (2017).
3. For a review, see N. C. Keim et al., https://arxiv.org/abs/1810.08587.
4. D. Fiocco, G. Foffi, S. Sastry, *Phys. Rev. Lett.* **112**, 025702 (2014).
5. K. H. Nagamanasa et al., *Phys. Rev. E* **89**, 062308 (2014).
6. P. Leishangthem, A. D. S. Parmar, S. Sastry, *Nat. Commun.* **8**, 14653 (2017).

A strain-based antenna paves the way for portable long-range transmitters

The piezoelectric device improves on the efficiency limits of small, conventional metal antennas without sacrificing bandwidth.

Very low-frequency (VLF) radio waves can carry signals through land and water with little attenuation. Unlike higher-frequency electromagnetic waves used for most communications, VLF waves are reflected by the ionosphere, and the space between it and Earth's surface acts as a waveguide through which the waves travel beyond the horizon. So, whereas higher-frequency waves travel in straight lines, VLF signals follow Earth's curvature and can transmit information to locations hundreds of kilometers away. The military uses VLF waves for navigation and communication with aircraft and submarines.

Although VLF signals are routinely generated, their use is limited by an antenna's size. To be reasonably efficient, an antenna's length should be at least a tenth of the signal's wavelength. For VLF waves, which are 3–30 kHz, the length would be more than a kilometer. Antennas whose length is much less than the signal's wavelength are considered "electrically small." They can still transmit VLF waves, but their nonradiative losses are large compared with the signals they transmit, so electrically small antennas are much less efficient than their larger counterparts. The VLF antennas used by the military are hundreds of meters tall, and even at that size they're electrically small. If they were portable, VLF antennas could be used by divers underwater, or by soldiers moving through underground mines or caves.

With their new piezoelectric antenna, Mark Kemp and coworkers at SLAC and their two industrial collaborators, SRI International and Gooch and Housego, are trying to get the best of both worlds.[1] Their prototype 9.6-cm-long lithium niobate transmitter, shown in figure 1, is much smaller than the approximately 10 km wavelength of the signal it generates, but it is more efficient than similarly small metal antennas. Although increased efficiency would normally be accompanied by a reduced bandwidth, modulating the antenna's resonant frequency allowed the researchers to maintain an effective bandwidth comparable to that of a small metal antenna.

Vibrating crystals

Piezoelectric crystals are often used as electronic oscillators because they vibrate with precise frequencies. Quartz crystals, for example, began being used about a century ago for timekeeping and as frequency references for radio sta-

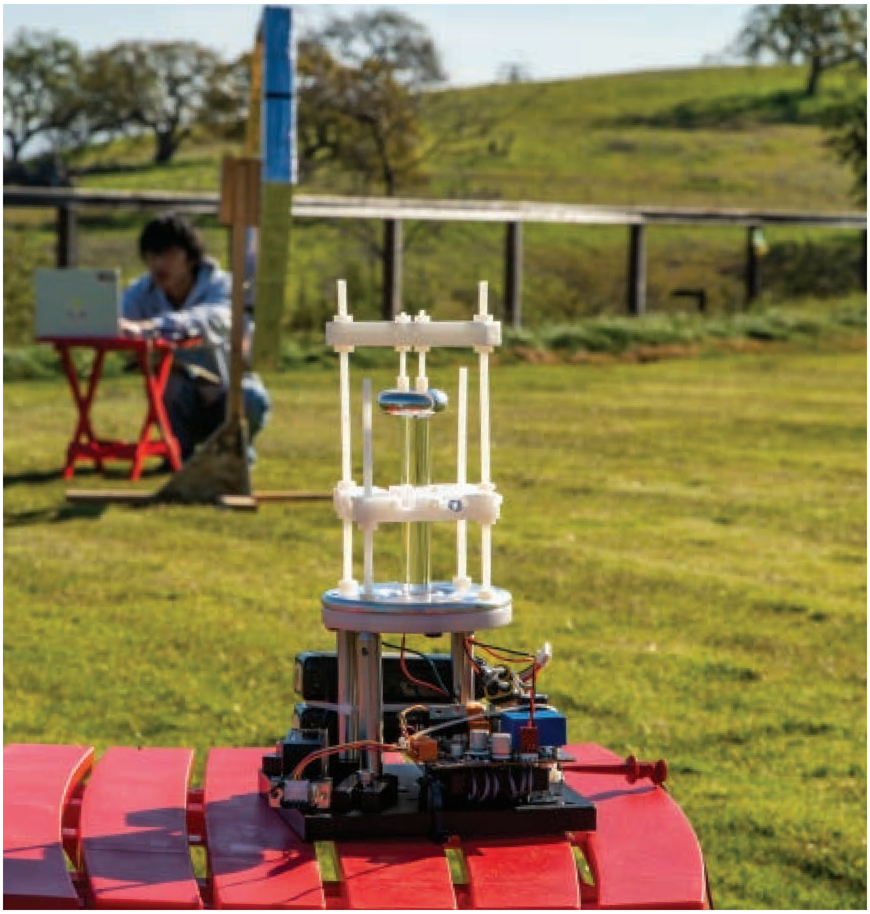

FIGURE 1. THE PORTABLE PIEZO-ELECTRIC TRANSMITTER in the foreground uses mechanical oscillations in a lithium niobate crystal (clear rod) to generate very low-frequency radio waves. Researchers had to take the transmitter to a remote location far from buildings and power lines to get accurate measurements of its field. In this photo, Alex Nguyen is using a receiver to measure and determine how the field drops off as a function of distance. (Photo courtesy of Dawn Harmer/SLAC.)

tions. Vibrations in piezoelectric crystals are generated by an electric field that causes the atoms to shift in each unit cell and thereby deform the crystal. That shift also causes charge separation, and a voltage difference develops between the ends of the crystal. When the field is removed, the crystal returns to its original state. Oscillating the electric field generates a periodic voltage and strain. If the field oscillates at the piezoelectric resonance of the crystal, which depends on its mechanical and electrical properties, the deformation and peak voltage are maximized. In a quartz watch, the timing of those voltage peaks determines the length of a second.

The $LiNbO_3$ crystal used by Kemp and colleagues works on the same principle. Applying an alternating voltage causes the crystal to vibrate at its resonant frequency. The vibration induces a large electric field in the crystal because of $LiNbO_3$'s strong electromechanical coupling. As the electric field in the crystal oscillates, the crystal radiates as an electric dipole, just like a wire antenna. However, whereas conventional antennas radiate because they carry a current of flowing charges, strain-based antennas radiate because of a displacement current, or time-varying electric field, created by bound charges in the material.[2]

Connecting an antenna directly to an impedance-mismatched power source causes signal reflection and the formation of standing waves in transmission lines.[3] Impedance matching the source and the antenna by adding the right combination of capacitors and inductors minimizes the problem and maximizes the power radiated by the antenna. But those additional circuit elements can be bulky and have their own associated losses. For a metal VLF antenna that would be small enough to carry, the size of and losses from the circuitry would be prohibitively large.

A piezoelectric resonator, however, eliminates the need for extra impedance-matching elements. The crystal behaves like an electrical circuit with a resistor, inductor, and capacitor, and the effective circuit's impedance can be tuned by varying the crystal's size, stiffness, and mechanical friction. A large impedance-matching inductance is therefore embodied by the antenna itself.

A measure of success

Radiation efficiency is proportional to the energy radiated and inversely proportional to its nonradiative losses. Switching to a piezoelectric material reduced the nonradiative losses in Kemp and coworkers' antenna by a factor of about 300 compared with a similarly sized metal antenna. That improvement came from using $LiNbO_3$, which has low mechanical elastic losses, removing the impedance-matching circuit, and choosing to excite a particularly low-loss vibrational mode in the antenna.

Reducing nonradiative losses should improve the overall efficiency of the antenna. But confirming that expectation requires measuring the radiated field at a distance comparable to the wavelength, which the researchers have not yet done. "Measuring the fields precisely is a challenge," says Kemp. "Any RF interference or materials around the transmitter and receiver can significantly alter the measurement. For many of our experiments, we had to go out to fields far

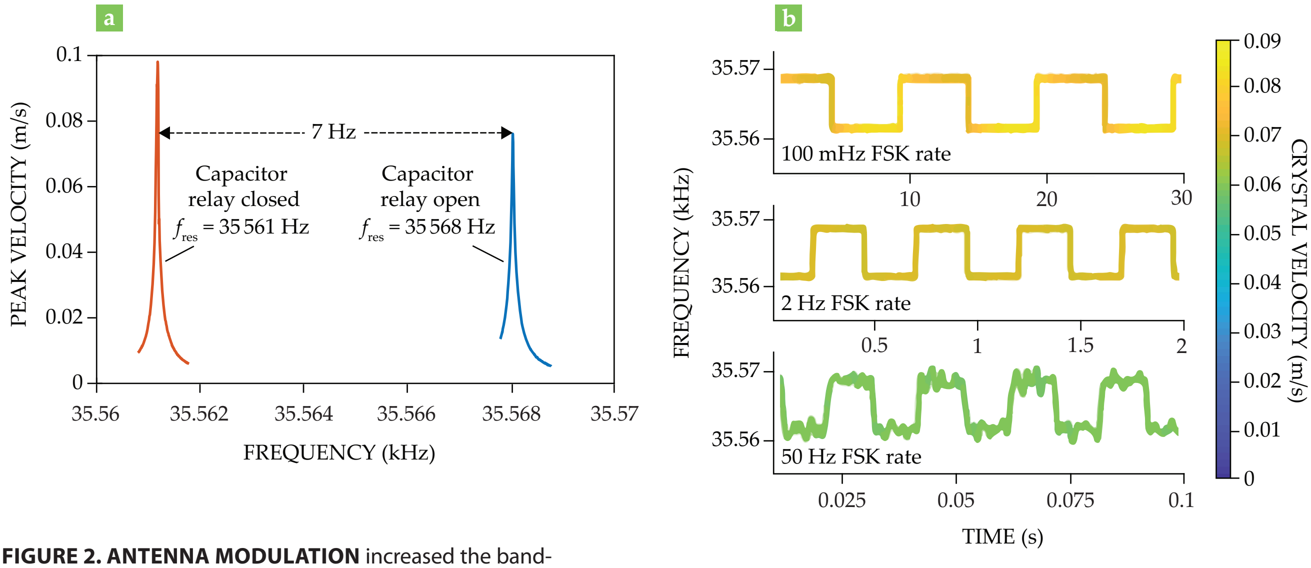

FIGURE 2. ANTENNA MODULATION increased the bandwidth of the piezoelectric transmitter. **(a)** Opening and closing a capacitor relay changes the resonant frequency f_{res} of the transmitter and allows it to oscillate at two easily distinguishable frequencies. **(b)** Frequency-shift keying (FSK)—alternating between two distinct frequencies—can encode information in narrowband signals. The transmitter's two resonant frequencies are easily distinguishable at all three FSK rates shown. However, at higher FSK rates, the velocity at which the crystal oscillates, and therefore the antenna's power output, decreases. (Adapted from ref. 1.)

away from power lines and buildings." Measurements of the field out to 80 m indicate that, like a metal antenna, the piezoelectric antenna radiates as a dipole. The researchers are therefore optimistic that upcoming far-field measurements will confirm their antenna's 300-fold increase in efficiency.

Reducing nonradiative losses is important for increasing efficiency, but unfortunately it also decreases the antenna's bandwidth. The piezoelectric resonator's bandwidth is just 84 mHz, which would be prohibitively small for using frequency modulation to transmit audio signals. Even large VLF antennas have limited bandwidths and are used only for text-based messages. Information is often encoded in the signal using frequency-shift keying (FSK)—alternating between two distinct frequencies. In that case, the transmitter doesn't need to work at a wide range of frequencies. It just needs to transmit strongly at two frequencies that can be distinguished from each other.

To improve the antenna's effective bandwidth—the separation between usable transmission frequencies—the researchers modulated its resonant frequency f_{res} between two values by coupling it to a capacitor through a relay. Modulating f_{res} between 35.561 kHz and 35.568 kHz, as shown in figure 2a, gave the antenna an effective bandwidth of 7 Hz, which is 83 times as large as the intrinsic bandwidth of one of the resonances. The two peaks are far enough apart that modulation between them can easily be distinguished, as shown in figure 2b. The signal starts to degrade at higher FSK frequencies that are similar to those typically used in VLF transmissions; the researchers suspect that effect is due to the speed of the relay that connects the external capacitor in the current prototype.

Like all antennas, piezoelectric antennas are inherently reciprocal, meaning that they can serve as both transmitters and receivers. But antenna modulation breaks that reciprocity. If the resonant frequency of the antenna isn't modulated along with the transmitter, it will only receive one of the frequencies. But knowing when to modulate the receiver would require already knowing the incoming signal pattern. Small conventional receivers already exist though, so the lack of reciprocity is not a problem.

The next phase

Although strain-powered antennas were first proposed more than 50 years ago,[4] Kemp and his collaborators took up the project recently thanks to the A Mechanically Based Antenna (AMEBA) program. Announced by the Defense Advanced Research Projects Agency in 2016, the AMEBA program drives fundamental research into mechanical antennas and antenna miniaturization, an area that hasn't seen much progress in recent years.[5] In line with the program's goals, Kemp says, "We target human-portable, long-distance communication with as small of a package as possible."

The researchers' project recently moved out of exploratory phase I and into developmental phase II, so they expect to continue pushing the limits of electrically small antennas. "At each phase, we will further increase the bandwidth and radiated power," says Kemp. A larger frequency separation would allow for better signal quality at higher FSK rates and give the researchers more flexibility in choosing a modulation scheme. In the coming year, they expect to improve both metrics by a factor of 10.

Christine Middleton

References

1. M. A. Kemp et al., *Nat. Commun.* **10**, 1715 (2019).
2. J. P. Domann, G. P. Carman, *J. Appl. Phys.* **121**, 044905 (2017).
3. J. S. Seybold, *Introduction to RF Propagation*, John Wiley & Sons (2005).
4. J. H. Rowen, F. G. Eggers, W. Strauss, *J. Appl. Phys.* **32**, S313 (1961).
5. Defense Advanced Research Projects Agency, "Underwater radio, anyone?" (16 December 2016).

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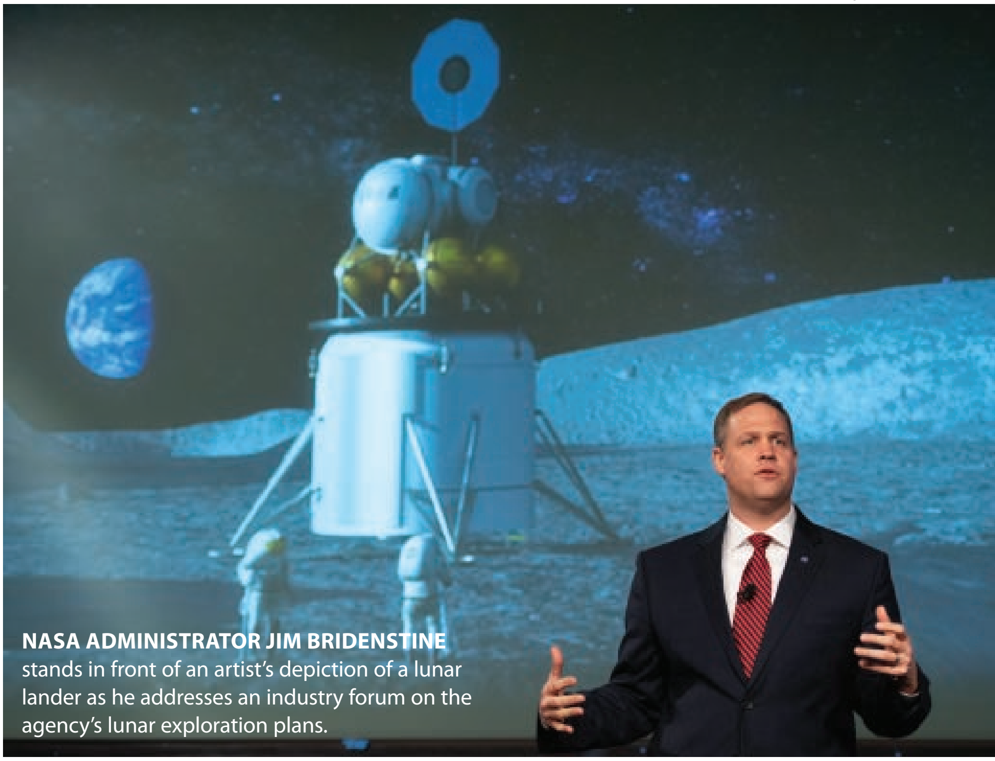
Quo vadis, NASA: The Moon, Mars, or both?

Fifty years after *Apollo 11*, the US spaceflight program is juggling political and technological factors as it moves toward the red planet, its ultimate destination.



NASA

NASA ADMINISTRATOR JIM BRIDENSTINE stands in front of an artist's depiction of a lunar lander as he addresses an industry forum on the agency's lunar exploration plans.

President Trump, NASA's leadership, Congress, and advocates for human space exploration agree that Mars should be the ultimate destination for the US spaceflight program. But will the administration's plan to send astronauts back to the Moon advance a Mars mission, or could the lunar program draw resources away from Mars and thus delay an excursion to the red planet?

In March of this year, Vice President Pence announced the administration's decision to move up by four years, to 2024, its target date for sending astronauts, including the first woman, to the Moon. But congressional appropriators' rejection of the administration's request to add $1.6 billion to NASA's fiscal year 2020 budget to accelerate the Moon landing program casts doubt on the 2024 goal.

Trump's December 2017 executive order, Space Policy Directive 1, acknowledged the goal of getting to Mars even as it ordered a return to the Moon. The 2017 NASA authorization act—which does not provide funding—also confirmed Mars as the ultimate destination for human exploration.

Regardless of exactly when it may happen, is putting humans back on the lunar surface truly a prerequisite for going to Mars? "I wish I could give you a really crisp, black and white answer, but it is a bit nuanced," says Scott Hubbard, who was director of NASA's Ames Research Center and NASA's first Mars program manager.

"This debate has been going on for decades," says Hubbard. "You can make a solid case that you can send people to Mars with only minimal testing at the Moon." As far back as 1991, aerospace engineer Robert Zubrin and colleagues at Martin Marietta (now Lockheed Martin) floated a Mars Direct plan, which eschewed a return to the Moon and the associated components of NASA's proposed lunar and Martian flight architecture.

Hubbard points to another proposal by three scientists at NASA's Jet Propulsion Laboratory (JPL) in 2015. It relied heavily on a set of elements already built or planned by NASA, such as the Space Launch System (SLS) heavy-lift rocket, the four-person Orion capsule, a deep-space habitat, and a 100 kW solar-electric-propelled "tug" for transporting supplies ahead of a human landing. The plan entailed few if any operations on the lunar surface and avoided complicated development programs such as nuclear-thermal propulsion. The JPL proposal envisioned an initial human mission landing on Phobos, the larger of Mars's two moons, in 2033, with a Mars touchdown in 2039.

More recently, SpaceX has proposed flying humans directly to Mars aboard its planned "starship." Paul Wooster, SpaceX's principal Mars engineer, told the Humans to Mars Summit (H2M) in May, "It's not unreasonable" that the company will put people on the planet by the mid 2020s.

Jonathan Lunine, a Cornell University astronomer who cochaired a National Academy of Sciences (NAS) review of NASA's human spaceflight program in 2014, says that "from a strictly engineering point of view," a direct-to-Mars approach is feasible. "But you increase the risk tremendously, from two points of view: One, you're not going to be testing a lot of technologies until you actually get to Mars; and two, politically, because you don't have an intermediate goal in a program that is going to stretch significantly in time beyond what Apollo was."

Returning to the Moon would build momentum in a human spaceflight program that hasn't ventured beyond low-Earth orbit since the Apollo program ended in 1972. "If we wait until Mars, the whole government spaceflight program will collapse of its own weight," says John Logsdon, emeritus professor of space policy at George Washington University. "There's a pretty convincing case for making the Moon a first goal, but not the last goal."

Ken Bowersox, deputy associate administrator for NASA's human exploration and operations mission directorate, told H2M attendees that "everything we do [on the Moon] is intended to inform our journey to Mars." A timetable for when humans could make such a trip could come as soon as 2025, he said.

An alternate route

"Mars is the ultimate destination for human exploration of the inner solar system; but it is not the best first destination," concluded the 2009 report of an advisory committee commissioned by the Obama administration. The findings of the panel, chaired by retired Lockheed Martin CEO Norman Augustine, led to the administration's decision to excise the Moon as a destination for NASA's exploration program (see PHYSICS TODAY, December 2009, page 25). The committee advised that alternate destinations—a lunar orbit, an asteroid, or a Lagrange point—were equally as useful as the surface of the Moon.

Obama chose an approach, outlined in the report, of sending a crewed spacecraft into a stable orbit near the Moon, from which a manned mission would embark to a small asteroid. The rock would be physically redirected into an orbit near the Moon. In addition to being less expensive than landing on the Moon, a lunar orbiting spacecraft, the Augustine committee noted, could be a launching point for a Mars mission that would avoid the energy and fuel required to escape the Moon's gravity. But the asteroid-redirect plan garnered little support from scientists.

Obama science adviser John Holdren says the administration concluded that "there was little point in putting astronauts on the Moon again, more than 50 years after we did it the first time, unless we were going to do significantly more when we got there—meaning in our view setting up a crewed base." At the time, NASA estimated the cost of putting a crewed base on the Moon at $60 billion to $80 billion, he says. "We saw no prospect of such a sum materializing on any time scale of planning interest."

Although the Augustine panel said no viable human spaceflight program could be carried out for less than a $3 billion addition to NASA's budget, Holdren says Obama decided that the asteroid-redirect route could at least be started for an extra $1 billion per year, the amount of additional funding Obama was willing to request from Congress.

Holdren estimates NASA will have to find an additional $5 billion each year to meet its 2024 Moon-landing target.

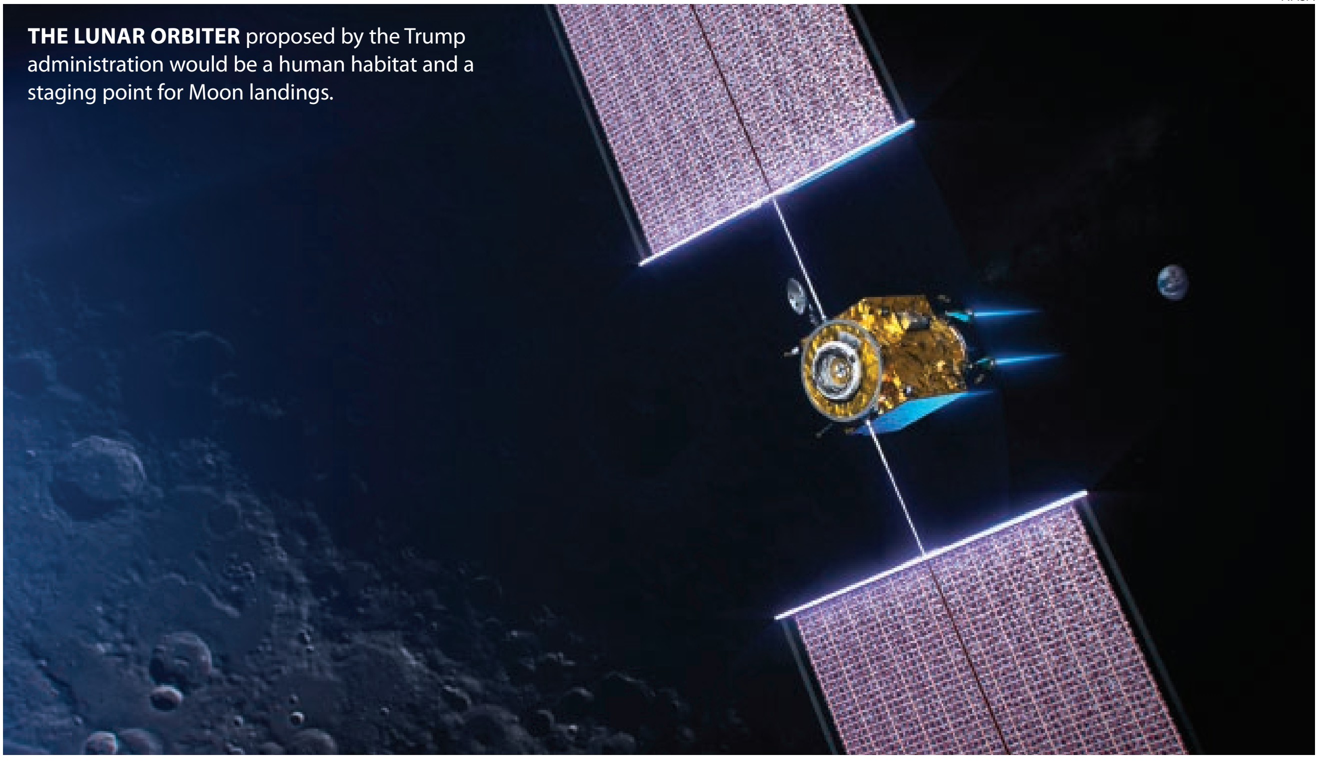
A proving ground

To NASA administrator Jim Bridenstine, who assumed NASA's helm in April 2018, the Moon is "the proving ground" and "the path to get to Mars in the safest, fastest way possible. When we accelerate humans to the Moon we are by definition accelerating humans to Mars," he told the H2M conference. In following Trump's directive, NASA plans to establish a permanently staffed outpost on the lunar surface in 2028.

William Gerstenmaier, NASA associate administrator for human exploration and operations, told the House Science, Space, and Technology Committee in May that the Moon "provides an opportunity to demonstrate new technologies that we will use on crewed Mars missions: power and propulsion systems, human habitats, in-space manufacturing, life support systems, and *in situ* resource utilization."

Clive Neal, a University of Notre Dame engineering professor and lunar exploration advocate, says going directly to Mars risks a repeat of the Apollo experience. Despite its success, Apollo was canceled due to its expense, and NASA

NASA



THE LUNAR ORBITER proposed by the Trump administration would be a human habitat and a staging point for Moon landings.

lacked any follow-on program. "You'll wind up doing a one-and-done," Neal says. "There won't be longevity or sustainability in a program." Unlike distant Mars, he adds, the Moon offers opportunities for commercial participation.

NASA in late May awarded 10-year contracts totaling $250 million to three companies to begin transporting nearly two dozen payloads of instruments and other equipment to the lunar surface in late 2020. The agency's FY 2020 budget request included $1 billion for development of lunar landers by the private sector. Billionaire Jeff Bezos recently unveiled a mockup of a lunar lander being developed by his company, Blue Origin, although he provided no design details.

The poles of the Moon could hold, in permanently shaded craters, millions of tons of water ice that could be used to produce liquid oxygen and hydrogen to fuel a Mars-bound spacecraft, Neal and other experts say. Developing that resource could obviate the need to transport fuel from Earth. Additionally, surrounding a spacecraft with a meter-thick coating of water could protect astronauts from radiation on the way to a Mars orbit, says Neal.

NASA plans to use the Moon program, which it calls Artemis, to demonstrate several major components of the proposed Mars mission architecture. They include the lunar-orbiting command and control platform, to be assembled in space, from which reusable landers would embark from and return to the Moon and where astronauts would be stationed for months at a time. The gateway, as the platform is known, could also be useful for assessing the psychosocial and physical effects of long-duration space travel beyond near-Earth orbit. NASA officials envision initial crew visits of up to 30 days to the gateway and longer visits as additional modules are delivered. NASA in May awarded a $375 million contract to Maxar Technologies of Colorado to build the first section of the gateway, the power and propulsion element. It's due for launch in 2022. At least one other section will be needed to accommodate the planned 2024 landing.

Last year, the Sixth Community Workshop for Achievability and Sustainability of Human Exploration of Mars, a group of 70 experts on lunar and Martian exploration and science operations, compiled a list of technologies required for Mars that would benefit from experience gained from lunar operations. Among the transportation and propulsion needs were cryogenic propellant management, landers, and vehicle servicing and refueling. Operations on the Martian surface that could be advanced with knowledge from the Moon included human health and biomedicine, power systems, manned exploration rovers, and space suits. Others were *in situ* resource utilization—essentially living off the land—communications, and habitats and labs. The 2014 NAS report listed entry, descent, landing, advanced in-space propulsion and power, and radiation safety among key requirements for a Martian mission.

NASA

THIS SELF-PORTRAIT OF THE MARS *CURIOSITY* ROVER at a location known as Mount Sharp shows the dusty and rocky terrain that future astronauts may encounter. For scale, the rover's wheels are 50 centimeters in diameter and about 40 centimeters wide.

The proposed 2024 Moon landing will use the SLS and the Orion crew vehicle. Both were designed with lunar travel in mind. The first crewed flight of the SLS–Orion system is planned to orbit the Moon in 2022. The Government Accountability Office (GAO) reports that as of September 2018, the cost of the SLS, which NASA had scheduled for its initial launch last November, had grown by $1 billion, or 10% over its 2014 baseline estimate, and will not meet its rescheduled June 2020 launch target. NASA officials remain hopeful of an SLS launch late next year. Orion, which was supposed to fly uncrewed atop the SLS last fall, was at least $379 million, or 6%, over budget as of mid 2018, according to the GAO. Prime contractor Lockheed Martin expects further cost growth.

Maintaining focus

The NAS report stressed that systems developed for the Moon or other intermediate destinations should keep the Mars mission in mind. Lunine and others worry that relevance to Mars may be "traded away" in a sprint to get to the Moon by 2024. "The danger is that we will end up repeating an Apollo style landing on the Moon as an accomplishment in itself, and once again that will be the end," Lunine says, mirroring Neal's concern. Once humans return, "people will say that's great, what's next? And the what's next is you would have to start from scratch, and there's no impetus to start from scratch."

Casey Dreier, chief advocate and senior space policy adviser at the Planetary Society, agrees. "You have to have very disciplined, focused, and deliberative decisions made on what to do if Mars is your long-term goal. If you say we have to land in 2024, do you really have the time or ability to focus on how that will work in a Mars environment? Probably not."

Going to the Moon "would still represent a remarkable increase in capability from what we have right now for human spaceflight," Dreier says. "I'll happily see humans walking on the Moon if that means getting out of low-Earth orbit."

Another problem with NASA's current course, says Hubbard, is the high cost of maintaining humans in space, as evidenced by the more than $3 billion NASA spends on the International Space Station (ISS) each year. The maintenance burden on NASA's budget will grow much greater if a permanent habitation is set up on the Moon, and that will leave far less money for a Mars development program, he notes.

Key differences between Moon and Mars environments won't allow for direct transfer of some elements, such as landers and manned rovers. Martian surface gravity is 38% of Earth's, compared with the Moon's 17% terrestrial fraction. Mars's atmosphere provides some protection from radiation, whereas the Moon's does not. Although dust is a hazard for humans and equipment on both bodies, dust storms occur only on Mars.

The NAS cautioned against wasting NASA resources and time on "dead-end" development programs that won't be of use on Mars. Notably, the academy listed the single-use descent stage of the lander design for the 2024 lunar surface mission.

Propulsion systems are likely to differ from one destination to the other. Whereas the SLS–Orion system is conventionally fueled, NASA is eyeing both solar-electric and nuclear propulsion for Mars travel. The NAS study recommended nuclear propulsion for Mars travel, saying the power levels of the best solar-electric systems are far too low to use in human transit. Specifically, it called for developing both nuclear-thermal, in which a fluid such as liquid hydrogen is heated to high temperature to create thrust, and nuclear-electric, in which electricity generated by a nuclear reactor is used to drive a propellant at high speed. Neither has been deployed in space.

The two technologies are separate from radioisotope thermal generators, a nuclear technology that has powered more than two dozen spacecraft since the 1960s. Those devices generate thermal energy from the radioactive decay of plutonium-238, but aren't powerful enough for propulsion. (See PHYSICS TODAY, December 2017, page 26.)

Time-frame estimates for a crewed Mars landing range from 2033 to the 2040s and beyond. The launch window to the quickest path to Mars opens only every other year. The Science and Technology Policy Institute (STPI), which supports the White House Office of Science and Technology Policy, concluded that 2037 would be the earliest feasible date and 2039 the more likely date for a launch to the red planet. It said that 2033, the date proposed in the 2017 NASA authorization act, "is infeasible under any budget scenario and technology development and testing schedules."

The NAS report committee estimated that the earliest crewed surface mission to Mars will occur between 2040 and 2050, assuming that the ISS is extended to 2028 and that the human spaceflight budget is increased at twice the rate of inflation.

The STPI put the total cost of a NASA spaceflight program leading to a Mars landing in 2037 at $217 billion, including $121 billion devoted to Mars-related hardware development. Of the total, $34 billion has been spent to date for the SLS and Orion programs. Lunine was less definitive when he told a House hearing in May that it would require hundreds of billions of dollars.

Although Bridenstine and other officials have repeatedly insisted that the cost will be shared with international partners, there have been few if any specifics. If the US wants to reduce the cost, says Lunine, "it will need the kind of international contributions that we have never seen before in human-piloted programs." For example, the US has borne 85% of the cost of the ISS and even pays for seats on Soyuz flights to the station. Moreover, he and others note, relations with China have deteriorated to the point that cooperation may not be possible. The other big challenge, Lunine adds, is how to cooperate with other nations without giving away US technologies.

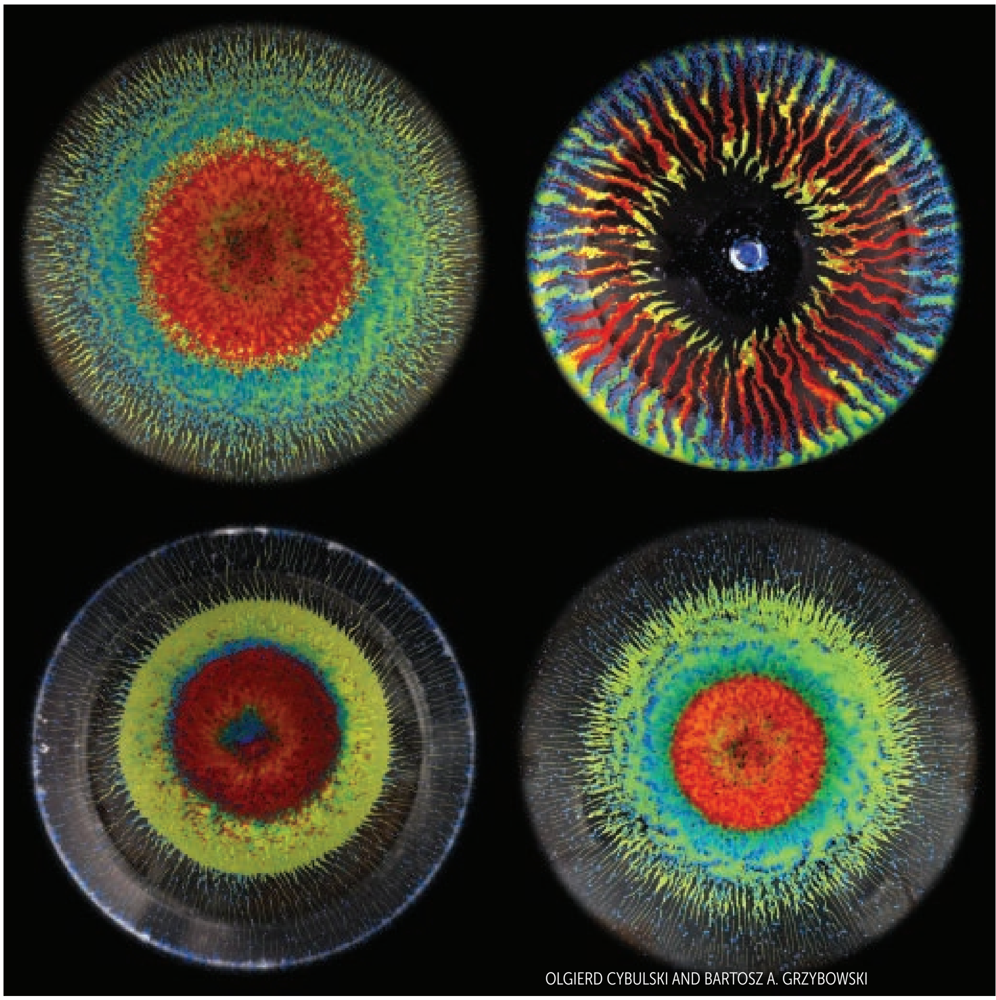
David Kramer

Domestic quarrels cloud future of South Korea's Institute for Basic Science

The country's network of curiosity-driven research centers is a scientific and cultural experiment.

Since its founding in 2011, the Institute for Basic Science (IBS) in South Korea has largely lived up to its ambitious goals. It has attracted top scientists, produced world-class science, and made inroads in internationalizing the country's research community. For continued success, however, the IBS must win over both the country's other scientists and its current politicians and convince them that the big federal investment in a relatively small number of investigators is worthwhile.

When the IBS was created, South Korea had an impressive track record in applied science and manufacturing; the auto and electronics industries are examples. In launching the new initiative, the country's then president Myung-bak Lee noted that countries at the forefront of



OLGIERD CYBULSKI AND BARTOSZ A. GRZYBOWSKI

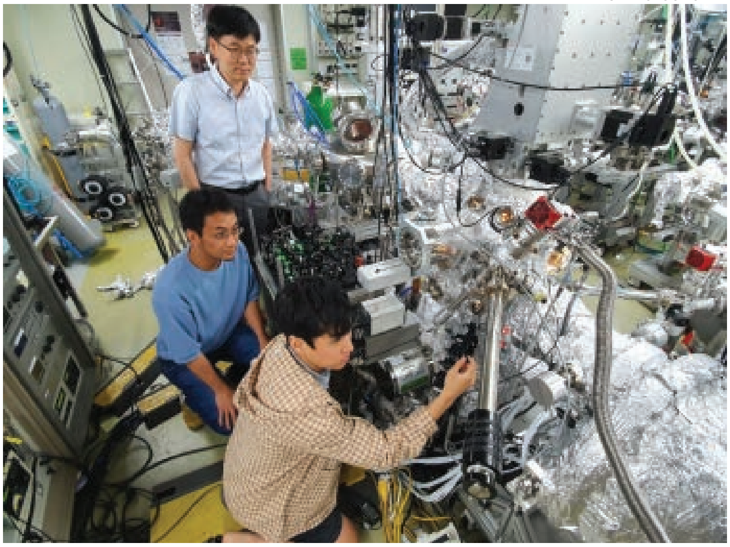
MICROPARTICLES SUSPENDED IN A ROTATING DENSE FLUID self-organize into dynamic patterns. Researchers at the Institute for Basic Science Center for Soft and Living Matter in South Korea study these nonequilibrium systems to gain insight into symmetry breaking and pattern formation in rotational frames of reference. The four images are snapshots with different rotational histories; they show the same mixture of three kinds of polyethylene microparticles that differ in density, size, and color.

science "have generated colossal national wealth on the strength of the achievements of basic research." He said that for South Korea to "emerge as an advanced, leading nation . . . we need to become a creative pacesetter based on basic science and original technologies."

And so the IBS was born. It was tasked with creating 50 research centers on a $600 million budget in its first five years (see PHYSICS TODAY, October 2012, page 26). The centers would look to Germany's Max Planck Institutes and Japan's RIKEN as models. They would be located on university campuses around the country and at IBS headquarters in Daejeon, about 150 kilometers south of Seoul.

Now the IBS is approaching a delicate juncture. In recent years the government has eroded the centers' budget and autonomy. And evaluations in the next year will determine whether the eight oldest centers will continue beyond 10 years. Those evaluations have many of the IBS directors on edge; the results will set the tone for the institute's future.

CHANGYOUNG KIM



SCIENTISTS AT THE CENTER FOR CORRELATED ELECTRON SYSTEMS are developing new laser systems. Student Yoonshik Kim (foreground) aligns laser optics, as Yukiaki Ishida (middle), a collaborator from Japan, and center associate director Changyoung Kim (back) look on. The center is one of 30 launched by South Korea's Institute for Basic Science.

"We are not held back"

The IBS currently consists of 30 centers across many scientific disciplines. Research topics are generally determined by the scientists, although some directors have been brought on to work in a specified thematic area. About one-quarter of the roughly 700 IBS researchers are foreigners, and a similar portion are women.

"We haven't grown as fast as we planned," says Se-Jung Oh, a condensed-matter physicist who served as the IBS's founding president. In some years no new centers were established; the most recent ones were started in 2017. Last year the IBS did launch two "pioneer" centers, a new model led by junior scientists with about one-quarter the budget and a shorter intended lifetime than the centers led by more senior scientists. "At least one or two full-scale centers should be established each year to signal to the world that the IBS is still growing," says Oh.

The center directors set the tone for the research and the organization. Steve Granick, who heads the IBS Center for Soft and Living Matter, strives to create a flat management structure and to hire scientists who are "creative, curious, get along with me, and have their own ideas." The chance to "have a new life scientifically and explore a new culture" lured him away from his 30-year tenure at the University of Illinois, he says. "The audaciousness of the IBS is amazing. Almost all of us are working on things that we were not working on before. We are not held back."

Yeongduk Kim is director of the IBS Center for Underground Physics, which has 65 researchers who are trying to identify dark matter and studying various aspects of neutrinos, such as whether they are their own antiparticles. The center is building a new underground lab about 1100 meters deep to shield it from cosmic-ray interference. The lab is slated to open in 2021 and will house a double-beta-decay experiment, a multipurpose scintillator for neutrino studies, and a scintillating crystal experiment with which, Kim says, "we will try to pinpoint low-mass dark-matter candidates."

Axel Timmermann moved in 2017 from the University of Hawaii to start the IBS Center for Climate Physics at Pusan National University. Two professors from the host university joined the center, and Timmermann is looking to hire three more. His center has enough money to employ 50 people. He and his colleagues use their supercomputer—the third-fastest in the country—to simulate future climate change and past ice ages. One goal is to predict the degree to which melting ice sheets will contribute to rising sea levels.

Another area of research at the center is how climate change affected past human migration and evolution. For that, Timmermann collaborates internationally with archaeologists, anthropologists, and geneticists. In addition to simulations, the project isotopically analyzes stalagmite samples collected from caves in South Korea. "The goal of the IBS is to do transformative research, stuff I can't do anywhere else. I am extremely happy that I can explore scientific frontiers and fringes that might be too risky for most places," he says.

Growing tensions

Resentment toward the IBS is growing, however, in South Korea's wider scientific community. Scientists at the centers have more funding than is available through individual investigator grants, and their funding is more stable and flexible. "The biggest risk to the IBS is from inside the country," says Andreas Heinrich, who leads the IBS Center for Quantum Nanoscience. "University scientists ask, 'Why should some people get more money? Why should Korea spend money on foreigners?'" The IBS was started with new money, but there is still a sense that the pie is not divvied up fairly.

The genesis of IBS exacerbates that envy. "It was initiated by a very small number of people and backed by a strong political decision," says Han Woong Yeom, director of the IBS Center for Artificial Low Dimensional Electronic Systems. "We need stronger research groups if we want to compete with emerging groups in China and other countries," he says. "But we had no good discussion within our scientific community about

ANDREAS HEINRICH

ANDREAS HEINRICH moved to South Korea from IBM Research–Almaden in California in 2016 to start the Institute for Basic Science Center for Quantum Nanoscience, which is housed at the Ewha Womans University in Seoul.

the needs and structure and identity of the IBS," he says. "This is generating more trouble as time passes."

"Resistance from the university science community is natural. They think it will weaken their position," says Peter Fulde, a former director at the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany, and one of 25 members of the IBS scientific advisory board. "The same phenomenon happened when the Max Planck Society's predecessor, the Kaiser Wilhelm Society, was formed in 1911." It's crucial to appoint outstanding scientists as directors, he says, and to give the new institute time to mature. Fulde says the IBS is so far living up to expectations. He recommends stable budgets, inclusion of more graduate students, stronger ties to the international community, and autonomy for center directors.

The South Korean government has changed twice since the IBS was formed. Due to the different policies of the parties in power and in response to grumbling from the country's broader scientific community, the growth of the IBS budget hasn't kept up with the increasing number of centers. Individual center budgets have decreased from an annual average of about $8.4 million early on to about $5.2 million this year. And since last year the government has required details of how centers use their funding, and officials say the directors have had too much flexibility, according to Yeom.

A rare isotope and heavy-ion facility, RAON, in the works in South Korea further confuses the situation. Both RAON and the IBS are part of a larger scheme called the International Science and Business Belt, and the IBS oversight of the $1.2 billion facility adds to the perception of money going to a select group of researchers, even though the accelerator is a separate project, says IBS president Doochul Kim. Slated to open to users in 2021, RAON has become something of an albatross for South Korea's science community and the IBS.

In an effort to appease non-IBS scientists, the South Korean government is doubling grant money for individual investigators over a five-year period, from about $1 billion in 2017 to $2 billion in 2022. In 2017 the country's total budget for basic research was $4.5 billion. The IBS received about $200 million. IBS scientists can't compete for grant money.

One IBS aim is for the methods and level of research at the centers to spill over into the country's wider scientific community. Many of the IBS facilities—including synchrotron beamlines, electron microscopes, and supercomputers—are open to other users. Some IBS center directors host workshops and conferences and pay for domestic students and faculty to attend. And some, like Yeom, hire young faculty members to help them launch their careers and to integrate them into the international groups—which tend to be less hierarchical than traditional research arrangements in the country. The IBS is the country's first scientific institution to be rated through a peer-review-based international assessment process. "The IBS is influencing the broader community," says Tae Won Noh, director of the Center for Correlated Electron Systems. "For example, the postdoc system is improving."

"The IBS has an identity problem," says Yeom, and the onus is on the directors to demonstrate that the institute is worth supporting. "What are the qualifications for a director? What distinguishes the role of IBS scientists from other researchers? And what is the optimal budget for an IBS center? Those questions need answers," Yeom says. An IBS center should do things that individuals cannot. The synergies among the researchers and the scale of the facilities should add up to more than the sum of the parts, says Heinrich. "The IBS is especially important for large projects and things that can't be done by single investigators," he adds.

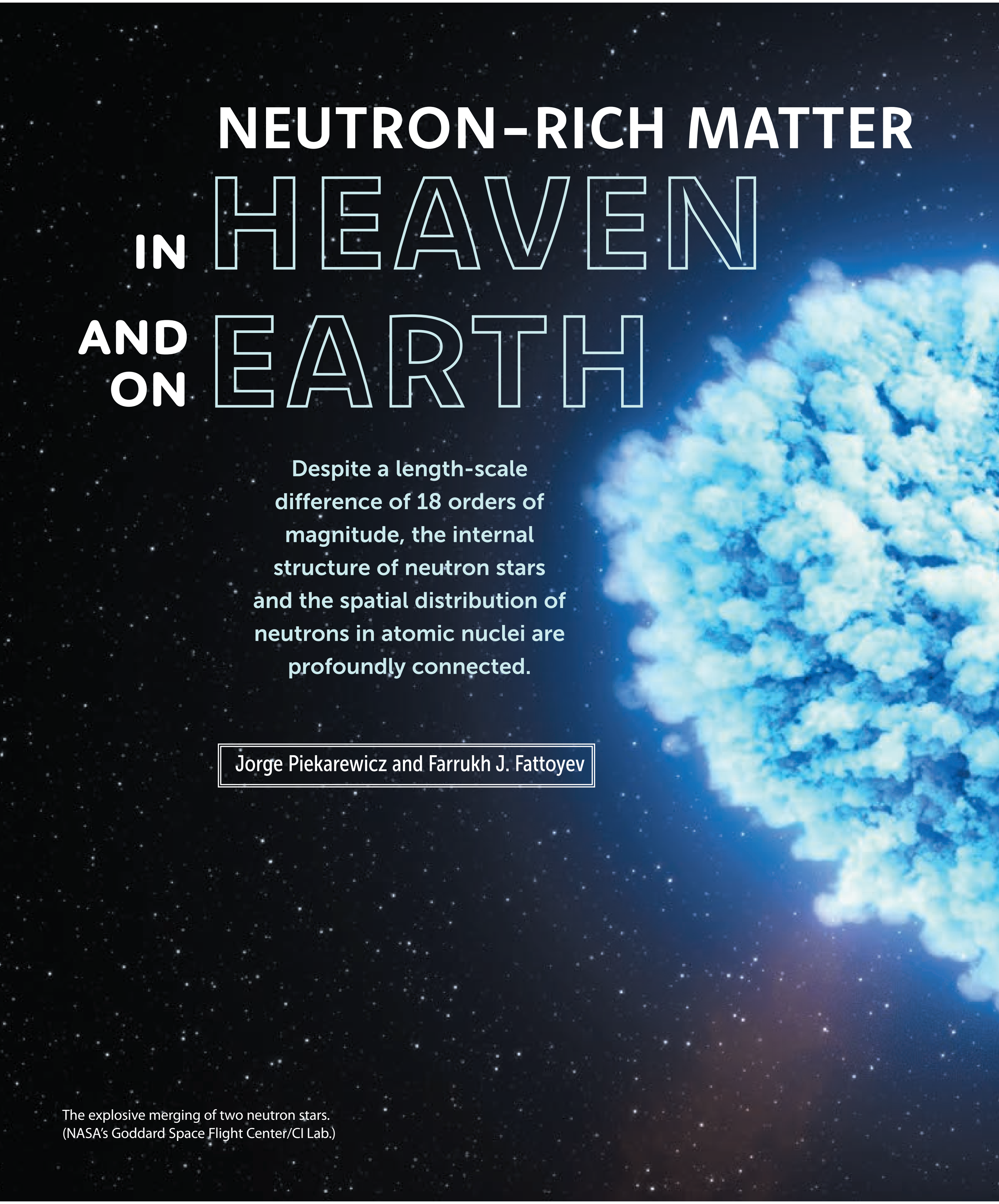
The IBS has "changed the paradigm of basic science" in South Korea, says the institute's president. "We often say it is a miracle that the IBS was realized at all." But it's a challenge, he says, to persuade policymakers to keep the original philosophy of the IBS, in which top scientists are given the resources and rein to pursue their ideas. Many variations for the future of the IBS are floating around, he adds. "The country needs to think seriously about what to do in the next five or 10 years."

Toni Feder PT

NEUTRON-RICH MATTER IN HEAVEN AND ON EARTH

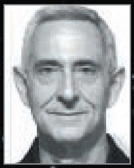
Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.

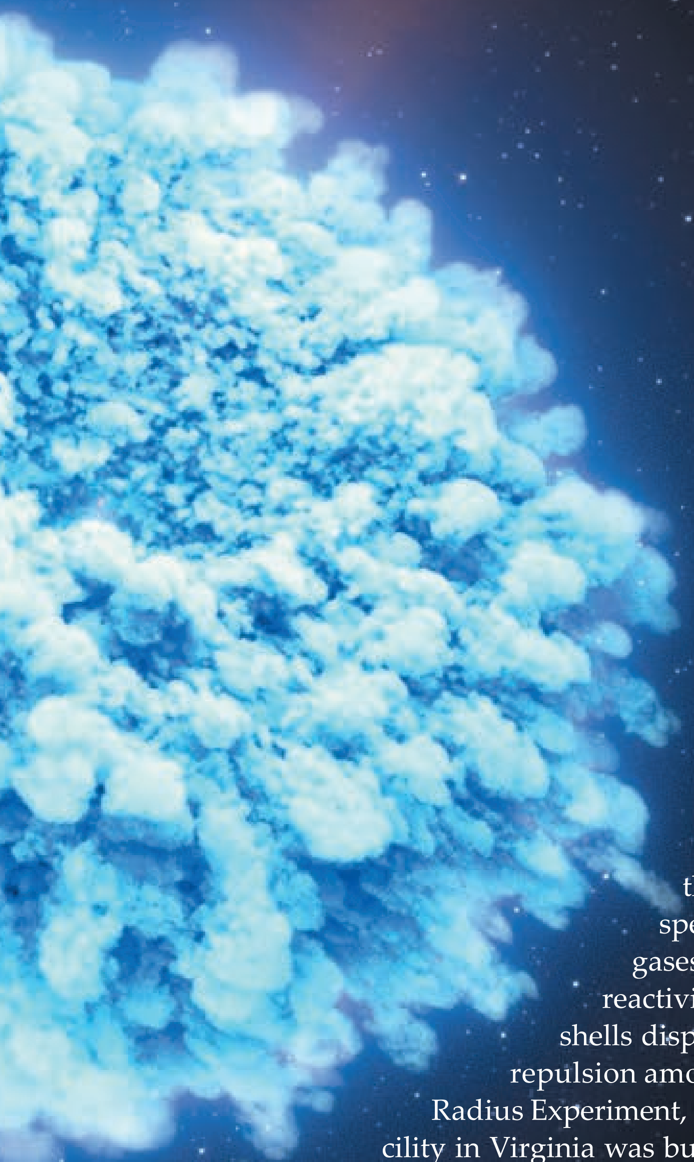
Jorge Piekarewicz and Farrukh J. Fattoyev



The explosive merging of two neutron stars.
(NASA's Goddard Space Flight Center/CI Lab.)

Jorge Piekarewicz is a professor in the department of physics at Florida State University in Tallahassee, and **Farrukh Fattoyev** is an assistant professor in the department of physics at Manhattan College in New York City.





Where do neutrons go? The elusive answer to such a seemingly simple question provides fundamental new insights into the structure of both atomic nuclei and neutron stars. To place the question in the proper context, consider lead-208, the element's most abundant isotope, which contains 82 protons and 126 neutrons. As the heaviest known doubly magic nucleus, ^{208}Pb holds a special place in the nuclear-physics community. Just as noble gases with filled electronic shells exhibit low levels of chemical reactivity, doubly magic nuclei with filled proton and neutron shells display great stability. Because ^{208}Pb is heavy, the Coulomb repulsion among its protons leads to a large neutron excess. The Lead Radius Experiment, or PREX, at the Thomas Jefferson National Accelerator Facility in Virginia was built to measure the location of ^{208}Pb's 44 excess neutrons.[1] In turn, a detailed knowledge of the neutron distribution in ^{208}Pb illuminates the structure of a neutron star.

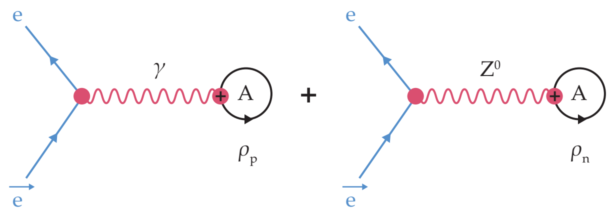


FIGURE 1. PROBING THE NEUTRON DISTRIBUTION. The Feynman diagram on the left illustrates the exchange of a photon between an electron and an atomic nucleus, and the one on the right shows the exchange of a neutral weak boson Z^0. The quantum mechanical interference of the two generates a difference in the cross section between right- and left-handed polarized electrons. The induced parity-violating asymmetry provides a powerful model-independent tool to probe the neutron distribution of neutron-rich nuclei.

To understand how the challenging measurement was made, consider the liquid-drop model[2,3] of George Gamow, Carl von Weizsäcker, Hans Bethe, and Robert Bacher, which they developed shortly after James Chadwick's discovery of the neutron. In the model, the atomic nucleus is regarded as an incompressible drop consisting of two quantum fluids. One is electrically charged and consists of Z protons; the other is electrically neutral with N neutrons. The radius of the charged drop—indeed, the entire proton distribution—has been accurately mapped since the advent of powerful electron accelerators in the 1950s. In contrast, knowledge of the neutron distribution comes entirely from experiments involving strongly interacting probes, such as pions and protons. Unlike experiments with electromagnetic reactions involving weakly coupled photons, those with strongly interacting probes are difficult to decode because of myriad theoretical uncertainties. PREX took advantage of the flagship parity-violating program at Jefferson Lab to infer the radius of the neutron distribution in ^{208}Pb.

In some parity-violating experiments, one measures the difference in the cross section between right- and left-handed longitudinally polarized electrons. In a world in which parity is exactly conserved, the parity-violating asymmetry would vanish. However, the weak interaction violates parity, so an asymmetry emerges from a quantum mechanical interference of two Feynman diagrams: a large one involving the exchange of a photon and a much smaller one involving the exchange of a neutral weak vector boson Z^0, as shown in figure 1. Whereas photons couple to the electric charge and are therefore insensitive to the neutron distribution, the Z^0 boson plays the complementary role. That is, the weak charge of the neutron is large compared with that of the proton,[4] which makes parity-violating electron scattering an ideal tool to determine the neutron distribution. PREX has provided the first model-independent evidence that the rms radius of the neutron distribution in ^{208}Pb is larger than the corresponding radius of the proton distribution.[1] The difference between those two radii is known as the neutron-skin thickness, a dilute region of the nucleus populated primarily by neutrons.

Neutron skins

Characterizing the neutron-rich skin in ^{208}Pb may help constrain nuclear models that aim to describe the nuclear dynamics of both atomic nuclei and neutron stars in a single unified framework. The link between the very small and the very large is particularly compelling given that a strong connection has been established between the thickness of the neutron skin of ^{208}Pb and the radius of a neutron star.[5] The dynamics behind such a correlation can be revealed by returning to the liquid-drop model, in which the nuclear binding energy is encoded in a handful of empirical parameters that represent volume, surface, Coulomb, and symmetry contributions:

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_a (N-Z)^2/A + \ldots.$$

The volume term a_v scales with the total number of nucleons $A = Z + N$, and that fact underscores both the short-range nature and saturation properties of the underlying nuclear force. A hallmark of nuclear dynamics is the existence of a saturation density of about $\rho_0 \approx 0.15\ \mathrm{fm}^{-3}$, which is close but not equal to the nearly constant central density observed in atomic nuclei. The next two terms represent corrections to the energy that result from the development of a finite nuclear surface a_s and the Coulomb repulsion among protons a_c. A quantum correction is applied for asymmetric nuclei because of the Pauli exclusion principle. The last term—the sym-

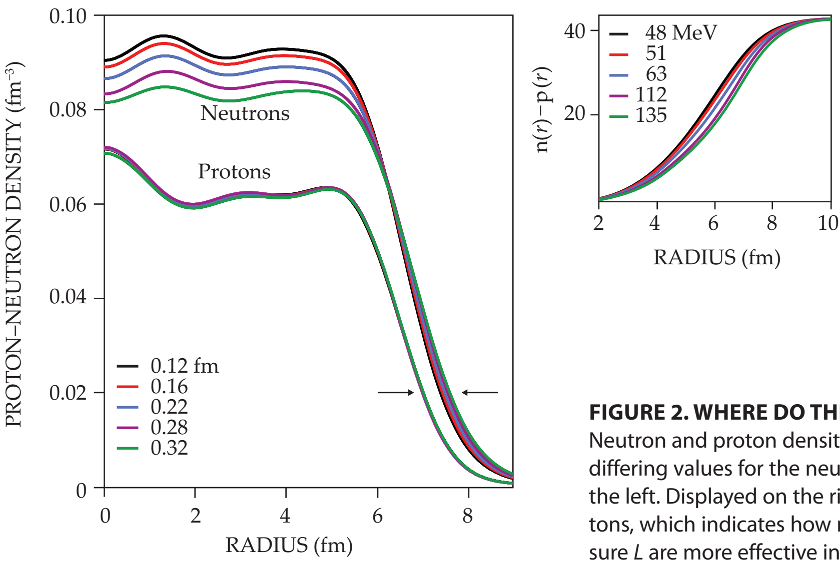
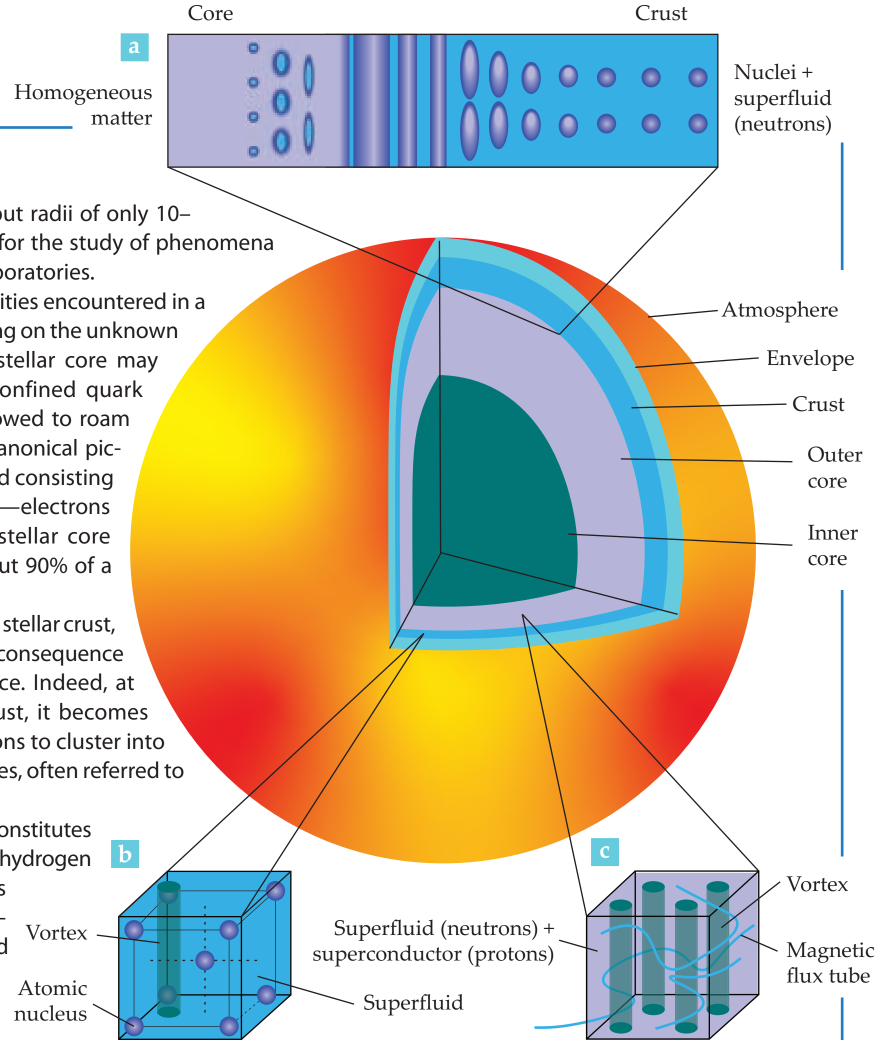


FIGURE 2. WHERE DO THE EXCESS NEUTRONS OF LEAD-208 GO? Neutron and proton densities in ^{208}Pb are predicted by various models with differing values for the neutron-skin thickness, as shown in the legend on the left. Displayed on the right is the running sum of neutrons minus protons, which indicates how models with larger values of the symmetry pressure L are more effective in pushing the 44 excess neutrons to the surface.

BOX 1. ANATOMY OF A NEUTRON STAR



With masses comparable to that of our sun but radii of only 10–15 km, neutron stars are unique laboratories for the study of phenomena that lie well outside the realm of terrestrial laboratories.

The stellar composition at the highest densities encountered in a neutron star's inner core is unknown. Depending on the unknown compressibility of neutron-rich matter, the stellar core may harbor exotic states of matter, such as deconfined quark matter, a novel state in which quarks are allowed to roam freely at enormously high densities. Yet the canonical picture of the stellar core is that of a uniform liquid consisting of neutrons, protons, and neutralizing leptons—electrons and muons—in chemical equilibrium. The stellar core accounts for practically all the mass and about 90% of a neutron star's size.

Above the uniform core lies the nonuniform stellar crust, a region about 1 km thick that develops as a consequence of the short-range nature of the nuclear force. Indeed, at the subsaturation densities of the stellar crust, it becomes energetically favorable for neutrons and protons to cluster into complex nuclei that display highly exotic shapes, often referred to as nuclear pasta.

The outermost surface of the neutron star constitutes the very thin atmosphere that is composed of hydrogen but may also contain heavier elements such as helium and carbon. To date, most of the information on neutron star radii has been obtained from the thermal emission from its surface, often assumed to be consistent with a blackbody spectrum. Unfortunately, complications due to both distortions to the blackbody spectrum and distance measurements make the determination of stellar radii a challenging task. Yet the discovery of gravitational waves from GW170817 has opened a new window into the study of neutron star properties and will nicely complement electromagnetic observations. (Image adapted from artwork by Dany Page.)

metry energy a_a and especially its density dependence—is crucial in connecting the neutron-skin thickness of atomic nuclei to the radius of a neutron star.

Although the liquid-drop model successfully describes the smooth variation of the nuclear binding energy with Z and N, the atomic nucleus is not an incompressible liquid drop. So although highly insightful, the semiempirical mass formula fails to capture the response of the liquid drop to changes in density. That information is embodied in the equation of state, which dictates how the energy depends on the overall density and neutron–proton asymmetry of the system.

In the thermodynamic limit and ignoring the long-range Coulomb interaction, the energy per nucleon at the equilibrium density is given entirely by the terms of volume a_v and symmetry energy a_a. The volume term a_v accounts for the dynamics of a symmetric system having equal numbers of protons and neutrons, whereas a_a penalizes the system for breaking the symmetry.

So what happens as the system departs from its equilibrium position? Changes to the energy per nucleon with density are imprinted in the pressure. However, the contribution to the pressure from the symmetric term vanishes at the equilibrium density. Thus the entire contribution to the pressure at saturation density comes from the symmetry pressure. Often denoted in the literature by L, the quantity is closely related to the pressure at saturation density of a system made entirely of neutrons; that is, $P_0 \approx L\rho_0 / 3$. The symmetry pressure, therefore, controls both the neutron-skin thickness of atomic nuclei and the radius of a neutron star.[6]

Connecting the very large to the very small

Where do the 44 excess neutrons in ^{208}Pb go? Although the liquid-drop model favors the formation of a spherical drop of uniform density, it is unclear what fraction of the excess neutrons should reside at the surface or in the core. Surface tension favors placing them in the core, which tends to minimize the surface area. But the symmetry energy, which is larger at the core than at the surface, disfavors that arrangement. Conversely, moving them to the surface increases the surface tension but reduces the symmetry energy. Thus the thickness of the neutron skin is determined by a tug-of-war between the surface tension and the difference between the symmetry energy at saturation density and at the lower surface density. That difference is nothing more than the symmetry pressure L. If the pressure is large, then energy considerations favor the excess neutrons to move to the surface where the low symmetry energy results in a thick neutron skin.[6]

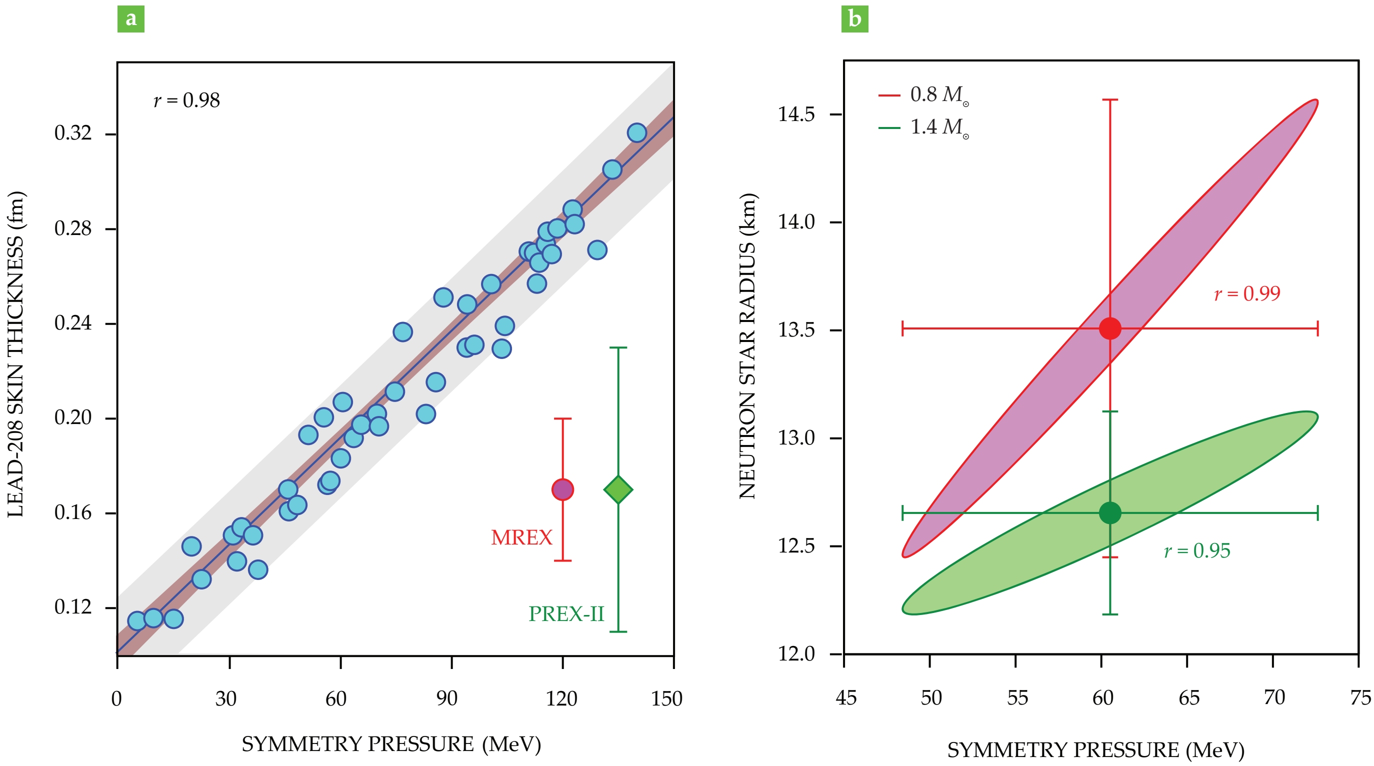


FIGURE 3. CONNECTING THE VERY SMALL TO THE VERY LARGE. The symmetry pressure *L* controls both the neutron-skin thickness of lead-208 and the radius of a neutron star despite the difference in size of 18 orders of magnitude. Many successful models illustrate the correlation **(a)** between *L* and the neutron-skin thickness of ^{208}Pb. (Adapted from ref. 7.) The correlation between *L* and the radii of two neutron stars **(b)** is illustrated for different masses.

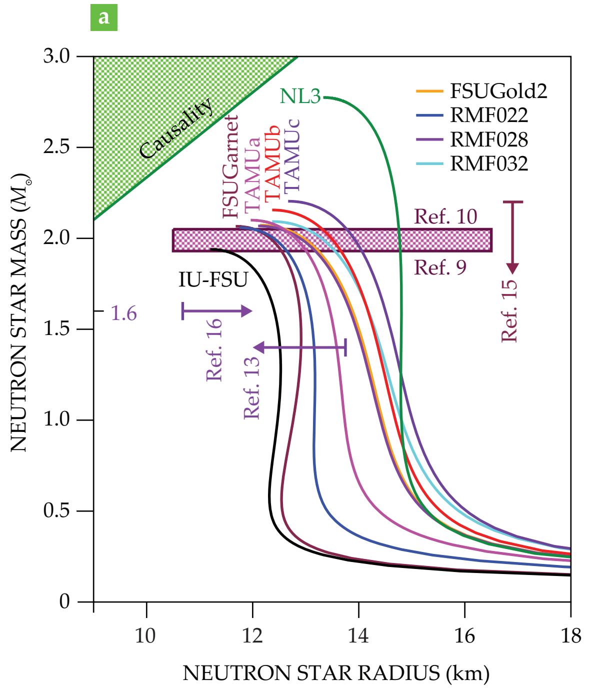
Where the neutrons go is nicely illustrated in figure 2, which displays neutron and proton densities for ^{208}Pb as predicted by various models that successfully reproduce properties of finite nuclei and neutron stars.[7] Given that the proton (or rather the charge) distribution of ^{208}Pb has been measured with remarkable precision, no significant spread is observed in the model predictions. Instead, challenging parity-violating experiments are required for a clean measurement of neutron densities. And although PREX has provided an important first step, the precision attained was insufficient to distinguish between the various competing models. The result means that a large model spread remains for the neutron densities and consequently for the neutron-skin thickness, whose values are indicated in the figure 2 legend on the left and schematically depicted by the region between the two arrows. The running sum, which naturally terminates at 44, represents the total number of excess neutrons accumulated up to a distance *r*. Models with a large symmetry pressure *L* push the excess neutrons farther out to the surface.

The strong correlation between the neutron-skin thickness of ^{208}Pb and the symmetry pressure *L* is evident in figure 3a, which shows predictions from a large number of models that utilize density functional theory in the spirit of the models[7] displayed in figure 2. With a Pearson correlation coefficient of nearly 1, the correlation is strong indeed. Such a result indicates how a fundamental parameter of the equation of state of neutron star matter can be measured in a terrestrial laboratory. The error bars in figure 3a indicate the precision anticipated for upcoming campaigns: PREX-II at Jefferson Lab and the Mainz Radius Experiment at the future Mainz Energy-Recovering Superconductor Accelerator at Johannes Gutenberg University.

Remarkably, it is the same symmetry pressure *L* that determines the radius of a neutron star, as shown in figure 3b. In that case, however, the symmetry pressure pushes against the immense gravitational attraction encountered in the stellar interior. Yet regardless of whether the pressure pushes against surface tension or against gravity, both the neutron-skin thickness of ^{208}Pb and the radius of a neutron star are sensitive to the symmetry pressure in the vicinity of saturation density. Despite a difference in size of 18 orders of magnitude, a powerful data-to-data relation emerges: The thicker the neutron-skin thickness of ^{208}Pb, the larger the radius of a neutron star. The correlation is particularly strong for low-mass neutron stars in which the interior density is only slightly larger than saturation density. As shown in figure 3b, the correlation coefficient weakens from $r = 0.99$ to $r = 0.95$ in going from a neutron star with solar mass of 0.8 to 1.4.

Neutron stars

Neutron stars are fascinating systems whose understanding requires a convergence of disciplines. Although the most common perception of a neutron star is that of a uniform assembly of neutrons packed to enormous densities, the reality is far dif-



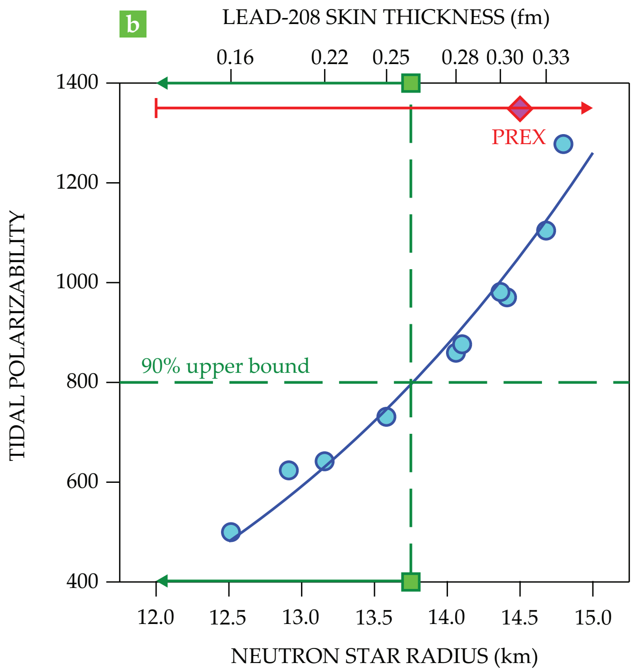


FIGURE 4. THE MASS-VERSUS-RADIUS RELATION (a) of neutron stars is reproduced by models (colored lines), which predict different stellar radii. Arrows indicate the limits that were obtained by combining electromagnetic and gravitational-wave observations. The rectangle defines the lower limits of the maximum stellar radius determined by photometry.[9,10] The other limits emerge from electromagnetic and gravitational-wave data from GW170817. Models predicting a maximum mass below the rectangle are inconsistent with observations. The green triangle denotes the forbidden area that violates causality, that is, faster-than-light speed of sound. The same models predict the tidal polarizability and radius **(b)** for a 1.4-solar-mass neutron star and the neutron-skin thickness of lead-208. Limits on the tidal polarizability inferred from GW170817 suggest that both the neutron star radius and the neutron-skin thickness are relatively small. However, the Lead Radius Experiment at the Thomas Jefferson National Accelerator Facility in Virginia reported a large value for the neutron-skin thickness of ^{208}Pb, albeit with large error bars. (Figures adapted from ref. 13.)

ferent and much more interesting. First theorized in 1933 by Walter Baade and Fritz Zwicky, neutron stars—or more precisely the radio pulses they emit—were detected in 1968 by a talented Cambridge graduate student named Jocelyn Bell Burnell. The achievement famously won her doctoral adviser, but not her, a share of the 1974 Nobel Prize in Physics.[8] Bell Burnell's contributions were honored in 2018 with the Special Breakthrough Prize in Fundamental Physics, and she has announced that she will donate the full $3 million award to programs that support diversity in the field.

Nuclear physics is important for elucidating the structure and composition of neutron stars (see box 1). Unlike white dwarf stars, which are entirely supported against gravitational collapse by the pressure from their degenerate electrons, neutron stars get critical pressure support from nuclear interactions. Indeed, in a 1939 paper, J. Robert Oppenheimer and George Volkoff demonstrated that a neutron star supported exclusively by neutron degeneracy pressure will collapse into a black hole once its mass exceeds 0.7 solar masses ($M_\odot$). Today, however, physicists know of at least two neutron stars with masses[9,10] as large as 2 $M_\odot$.

The surface of a neutron star, though largely insensitive to nuclear dynamics, is of observational importance because it significantly influences estimates of the stellar radius. Assuming that the thermal emission from the surface follows a blackbody spectrum at a uniform temperature, then the stellar radius may be determined from the Stefan–Boltzmann law, which relates the luminosity to the temperature and radius of the star. Unfortunately, the determination of stellar radii by photometric means has been plagued by large systematic uncertainties arising from unreliable distance measurements and from distortions to the blackbody spectrum from a thin stellar atmosphere. In the past, those uncertainties revealed discrepancies in the extraction of stellar radii as large as 5–6 km. (Average neutron star radii are 10–15 km.) Fortunately, the situation has improved significantly through a better understanding of systematic uncertainties, important theoretical developments, and the implementation of robust statistical methods.[11] And while the uncertainty has now been reduced to about a couple of kilometers, a powerful new player has entered the game: gravitational-wave astronomy.

Multimessenger astronomy

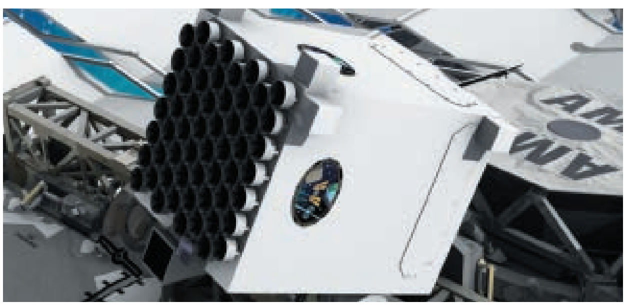
The first direct detection of gravitational waves, from a binary neutron star merger known as GW170817, by the collaboration of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo has begun a new era of multimessenger astronomy.[12] Besides gravitational waves, electromagnetic counterparts associated with both a short gamma-ray burst and a

BOX 2. HEAVEN AND EARTH

The neutron-skin thickness of atomic nuclei offers valuable insights into the nature of neutron-rich matter. Parity-violating electron scattering, a sensitive and powerful experimental tool perfected at the Thomas Jefferson National Accelerator Facility in Virginia, has been used to provide the first model-independent evidence in support of a neutron-rich skin in lead-208. Later this year the neutron-skin thickness of ^{208}Pb and calcium-48 will be measured with enough precision to constrain both nuclear models and the symmetry pressure *L*. To accomplish that ambitious project, state-of-the-art equipment—like the five-story-high spectrometer shown in the top figure—is essential. (Photo courtesy of DOE Jefferson Lab.)

On 17 August 2017, the collaboration of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo (shown in the second image) detected gravitational waves from the merger of two neutron stars known as GW170817. The detection provided critical insights for the synthesis of the heavy elements and the nature of neutron-rich matter—fundamental questions that scientists hope will be addressed by the mission of the Facility for Rare Isotope Beams (FRIB) currently under construction at Michigan State University. The LIGO–Virgo collaboration began its third operating run in April 2019, and the scientists anticipate detecting many more binary neutron star mergers. (Photo courtesy of Caltech/MIT/LIGO Lab.)

Two of the main science drivers of FRIB are the study of the heaviest elements and the production of exotic nuclei with thick neutron skins. In particular, FRIB will use strongly interacting probes to measure the neutron-skin thickness of short-lived isotopes. To ensure the success of such a challenging program, the upcoming electroweak measurements at Jefferson Lab will be instrumental in supplying critical calibrating anchors. The third image shows the progress on FRIB's high-power superconducting linear accelerator, which will propel heavy ions and produce rare isotopes by in-beam fragmentation. (Photo courtesy of Michigan State University.)



The Neutron Star Interior Composition Explorer (NICER) is part of NASA's first program dedicated specifically to studying the exotic structure and composition of neutron stars. Launched in June 2017 aboard SpaceX's Falcon 9 rocket, NICER was successfully deployed to the International Space Station, as shown in the bottom photo. By measuring radii of neutron stars, NICER will provide some of the most stringent tests of the equation of state of neutron-rich matter. NICER is a powerful complement to LIGO in this brand-new era of multimessenger astronomy. (Photo courtesy of NASA/CI Lab/Walt Feimer.)

long-term kilonova powered by the radioactive decay of *r*-process elements were also detected (see the article by Anna Frebel and Timothy C. Beers, Physics Today, January 2018, page 30). GW170817 has also provided fundamental new insights into the nature of dense matter.

Critical properties of the equation of state are encoded in the tidal polarizability, a property that describes the neutron star's tendency to deform in response to the tidal field induced by a companion star. The tidal polarizability is highly sensitive to the stellar structure and scales as the fifth power of the compactness. That quantity is defined as the ratio of the stellar radius to the Schwarzschild radius—that is, the radius at which the star would become a black hole. The Schwarzschild radius is directly proportional to the stellar mass; for our sun it is approximately 3 km. So, as two neutron stars approach each other, the phase of the gravitational wave deviates from its point-mass nature characteristic of black holes, and those deviations are imprinted in the tidal polarizability.

A fluffy or large-radius neutron star is much easier to polarize than a corresponding compact star with the same mass but a smaller radius. Given the sensitivity of the gravitational-wave signal to the neutron star structure, limits on the tidal polarizability inferred from GW170817 rule out overly large stellar radii and thereby provide a powerful complementary approach to the traditional photometric techniques.[13,14] Additional observational limits have been obtained on both the maximum stellar mass and the minimum radius of a 1.6 solar-mass neutron star.[15,16] As shown in figure 4a, the limiting values of stellar radii and maximum masses are now starting to paint a detailed picture of the mass-versus-radius relation.

A bright future

How do all the new developments illuminate the connection between GW170817 and atomic-scale laboratory experiments? In particular, given their sensitivity to the symmetry pressure, how do the inferred limits on stellar radii reflect on the neutron-skin thickness of ^{208}Pb? Considering that GW170817 disfavors overly large stellar radii, the inferred neutron-skin thickness is well below the central value measured by the PREX collaboration[13] and is clearly illustrated in figure 4b. To reduce the experimental uncertainty by a factor of three, the follow-up PREX-II experiment is scheduled to run at Jefferson Lab in 2019. After it and its sister campaign on calcium-48 are completed, the lab will pass the baton to the Facility for Rare Isotope Beams (FRIB) at Michigan State University that will study exotic nuclei with thick neutron skins.

A strong connection has been established between the thickness of the neutron skin of lead-208 and the radius of a neutron star.

The third observing run by the LIGO–Virgo collaboration began in April 2019 with the promise of many more detections of binary neutron star mergers. A PREX-II confirmation that the neutron-skin thickness of ^{208}Pb is large would imply that the symmetry pressure is also large or "stiff" at the typical densities found in atomic nuclei. If at the same time the LIGO–Virgo collaboration validates the relatively small stellar radii suggested by GW170817, then it will imply that the symmetry pressure is small or soft at about twice the saturation density. The evolution of the symmetry energy from stiff at typical nuclear densities to soft at slightly higher densities may indicate an exotic phase transition in the neutron star interior. In a recent reanalysis of GW170817 data, the LIGO–Virgo collaboration obtained limits on the tidal polarizability that are even more stringent than reported in the original discovery paper.

The determination of the symmetry pressure L—and more generally the density dependence of the symmetry energy—has far-reaching consequences in areas of physics as diverse as precision tests of the standard model using atomic-parity violation, the collision of heavy ions, and nuclear and neutron star structures. However, the search for new physics beyond the standard model is hindered by large uncertainties in the neutron radius, which, as previously discussed, is highly sensitive to L. Above saturation density, the symmetry pressure may be determined by means of experiments involving the collision of heavy ions, the only way to probe vast regions of the nuclear equation of state in terrestrial laboratories. Past experiments with energetic heavy ions enabled nuclear matter to be compressed to several times the nuclear saturation density and allowed researchers to extract the equation of state of symmetric nuclear matter. Current uncertainties in the density dependence of the symmetry energy are large, yet ongoing international efforts, such as the RIKEN Nishina Center for Accelerator-Based Science in Japan, FRIB, and the Facility for Antiproton and Ion Research at the GSI Helmholtz Center for Heavy Ion Research in Germany, are poised to probe neutron-rich matter at suprasaturation density and will offer a better understanding of its properties.

Although the multimessenger era is still in its infancy, the first observation of a binary neutron star merger is already providing a treasure trove of insights into the nature of dense matter. In the new era of multimessenger astronomy, the strong synergy between nuclear physics and astrophysics will grow even stronger. As illustrated in box 2, ultrasensitive gravitational-wave observatories, Earth- and space-based telescopes operating at various wavelengths, and new terrestrial facilities probing atomic nuclei at the limits of their existence are poised to answer 2 of the 11 science questions for the next century:[17] What are the new states of matter at exceedingly high density and temperature? How were the elements from iron to uranium made? The future is very bright indeed!

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REFERENCES

1. S. Abrahamyan et al. (PREX collaboration), *Phys. Rev. Lett.* **108**, 112502 (2012).
2. G. Gamow, *Proc. R. Soc. London* **126**, 632 (1930); C. F. von Weizsäcker, *Z. Phys.* **96**, 431 (1935).
3. H. A. Bethe, R. F. Bacher, *Rev. Mod. Phys.* **8**, 82 (1936).
4. Jefferson Lab Q_{weak} Collaboration, *Nature* **557**, 207 (2018).
5. C. J. Horowitz, J. Piekarewicz, *Phys. Rev. Lett.* **86**, 5647 (2001).
6. C. J. Horowitz et al., *J. Phys. G* **41**, 093001 (2014).
7. X. Roca-Maza et al., *Phys. Rev. Lett.* **106**, 252501 (2011).
8. A. Hewish et al., *Nature* **217**, 709 (1968).
9. P. B. Demorest et al., *Nature* **467**, 1081 (2010).
10. J. Antoniadis et al., *Science* **340**, 1233232 (2013).
11. F. Özel, P. Freire, *Annu. Rev. Astron. Astrophys.* **54**, 401 (2016).
12. B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo collaboration), *Phys. Rev. Lett.* **119**, 161101 (2017).
13. F. J. Fattoyev, J. Piekarewicz, C. J. Horowitz, *Phys. Rev. Lett.* **120**, 172702 (2018).
14. E. Annala et al., *Phys. Rev. Lett.* **120**, 172703 (2018).
15. B. Margalit, B. D. Metzger, *Astrophys. J. Lett.* **850**, L19 (2017).
16. A. Bauswein et al., *Astrophys. J. Lett.* **850**, L34 (2017).
17. National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, National Academies Press (2003).

PT

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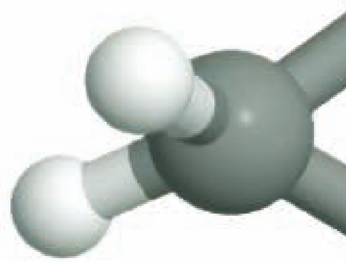
Designing clusters for HETEROGENEOUS CATALYSIS

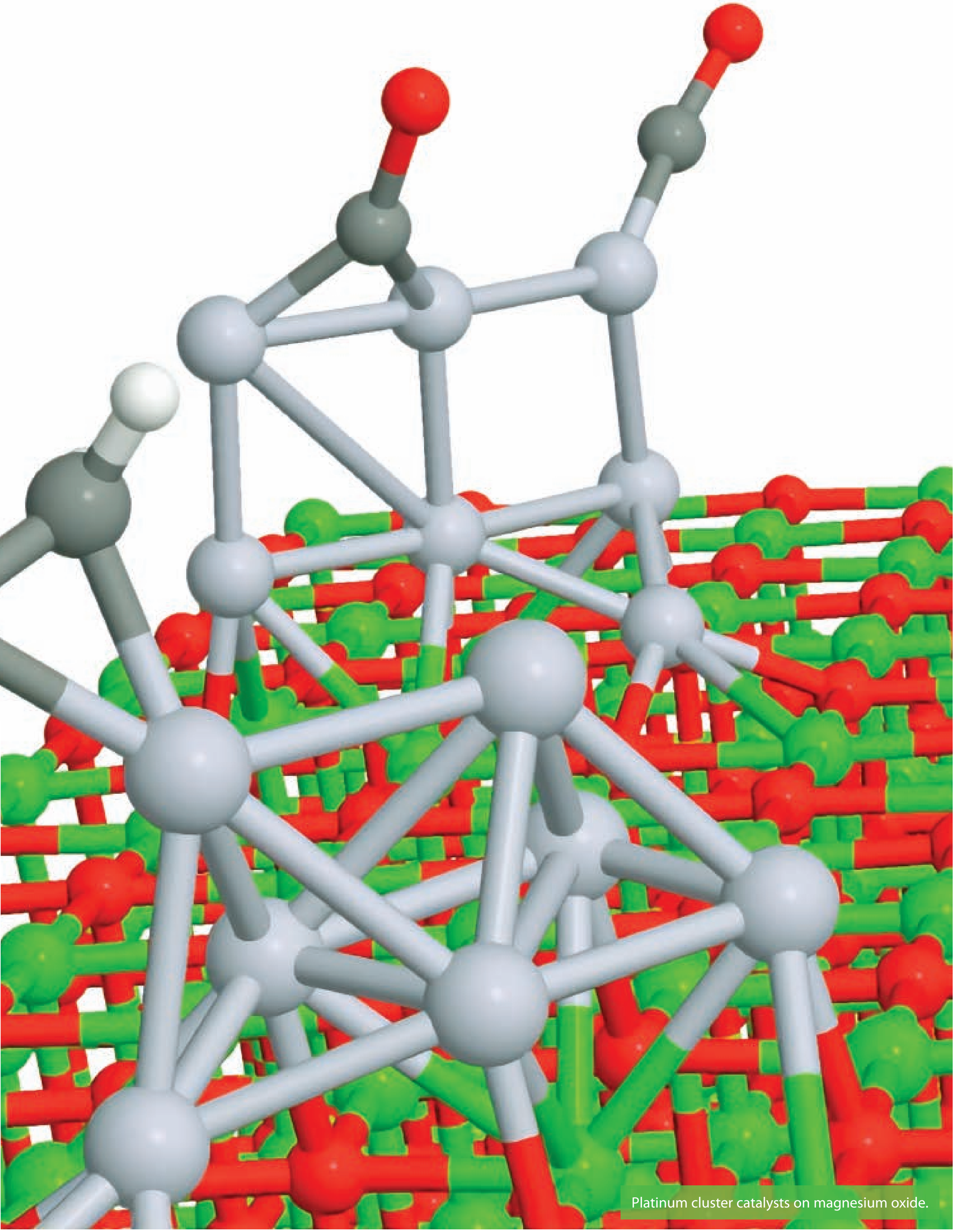


Elisa Jimenez-Izal,
Bruce C. Gates, and
Anastassia N. Alexandrova

Subnanometer metal clusters offer catalytic properties not possible on bulk or nanoparticle metals.

In 1987 Masatake Haruta and his colleagues at the Osaka National Research Institute in Japan reported on catalytic behavior of gold nanoclusters.[1] Theirs was not the first work to demonstrate metal nanoclusters as catalysts, but that discovery was striking given bulk gold's well-known chemical inertness. The startling change in the behavior of gold when its size was reduced drew renewed attention to the study of metal nanocluster catalysts.

Today catalysis is involved at some point in more than 90% of all chemical manufacturing processes. Most catalysts used for those and other large-scale processes—including fuel conversion and abatement of waste from vehicles and power plants—are porous, high-area solids with nanoparticles dispersed on the internal surfaces. Such catalysis is complex because it occurs on surfaces that are heterogeneous in both composition



Platinum cluster catalysts on magnesium oxide.

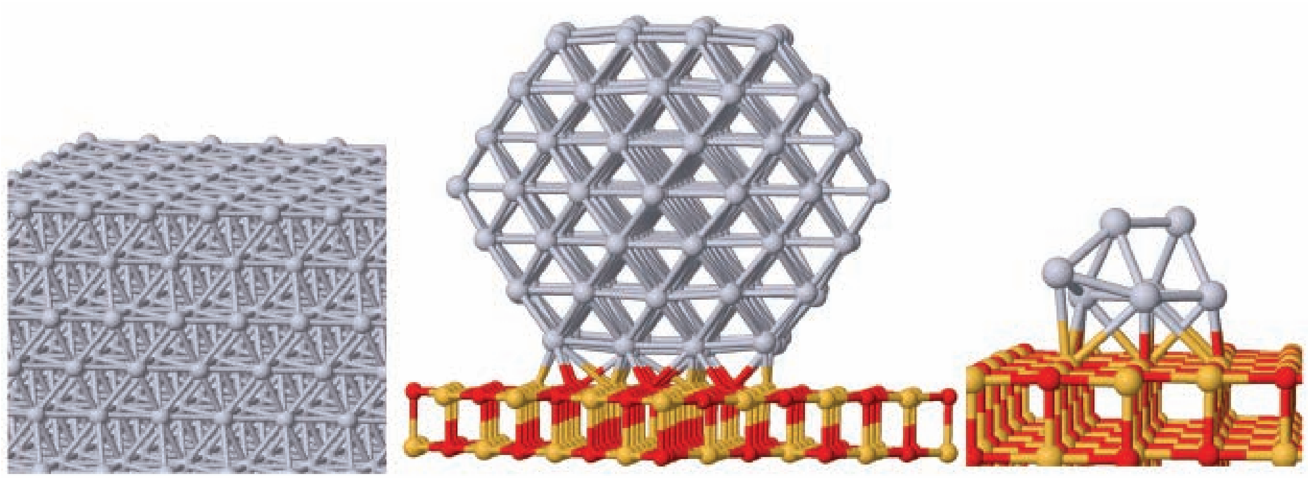


FIGURE 1. VARIOUS FORMS OF PLATINUM CATALYSTS. From left to right are bulk Pt(111), a Pt nanoparticle consisting of 146 atoms supported on magnesium oxide (100), and a seven-atom Pt cluster on MgO(100). In the cluster, all the Pt atoms are exposed and interact with reactants.

and structure. Thus technological advances are often the result of trial-and-error discovery. The dream for many catalysis researchers is first-principles design of catalysts with optimized properties, such as high efficiency, stable long-term operation, and regeneration after degradation caused by processes such as sintering and undesired side reactions, whose products block the surface.

The metals used in catalysts are often scarce and expensive, and only the metal atoms on the surface do catalysis. Subnanometer particles, called clusters, that consist of just a few atoms increase the surface area per metal atom. Figure 1 compares clusters with larger nanoparticles and bulk metals.

Manufacturers already use metal clusters as industrial catalysts—for example, platinum clusters on the order of 1 nm in diameter convert hydrocarbons, such as n-hexane and n-heptane, into aromatics, such as benzene and toluene. Surface-supported clusters of a few atoms and isolated atoms of platinum are also present in catalysis for the dehydrogenation of propane, a process that is one route to convert a component of shale gas into polymers and other chemicals.

The structures of those catalysts must be highly stable to be useful in industry. But metal nanoclusters on surfaces tend to coalesce into larger nanoparticles and lose catalytic activity as they lose surface area. They may be stabilized by metal–support interactions, as we discuss later. The reactions with metal clusters are different from those with the bulk metals, and they depend on the cluster size.[2]

Cluster reactivity

Manufacturers produce industrial catalysts by methods that are large scale and cost effective but imprecise. For example, an aqueous solution of tetraammineplatinum(II) nitrate, $Pt(NH_3)_4(NO_3)_2$, placed in contact with a porous metal oxide gives absorbed platinum salts that, when heated in air and then treated in hydrogen, are converted into platinum clusters and nanoparticles of various sizes, including isolated atoms. Because the resulting clusters and nanoparticles are not uniform, they are not ideal for investigations aimed at understanding how structure affects performance.

Researchers rely on synthesis methods that consistently produce clusters of the same size. One method uses a beam of vaporized metal that is chosen for a particular size of its gas-phase clusters. When the vapor hits a nonporous planar support, it deposits clusters; some are the same size as the gas-phase clusters, and some break apart on impact or coalesce. Alternatively, clusters stabilized with ligands—for example, $Os_3(CO)_{12}$ or $Ir_4(CO)_{12}$—react with metal oxide surfaces to produce supported clusters with some intact ligands that may be modified or removed. Although such methods are too expensive for practical application, they have opened the way to vibrant scientific literature that engages both experimentalists and theorists.

Researchers can determine the number of metal atoms per cluster using recent advances in scanning transmission electron microscopy that allow for atomic-resolution images of supported clusters when there is sufficient contrast—that is, for heavy metal atoms on supports consisting of light atoms. For example, images of triosmium clusters on crystalline magnesium oxide, in the top row of figure 2, show three clearly defined Os atoms[3] and indicate Os–support interactions.[4] When experimentalists pair the images with spectra, further evidence emerges of the metal–support interface and metal–metal and metal–ligand interactions. X-ray absorption spectroscopy and IR spectroscopy are among the most valuable spectroscopic methods.[2,3]

Even with the best-made samples and a full complement of tools, essential properties of supported metal clusters are beyond experimental reach. Computational modeling provides an in-depth picture of the properties of a polyatomic system and thus helps elucidate the relationship between structure and catalytic properties. Synergy between theory and experiment now drives the development of the field. Nevertheless, as we will discuss later, there are still important limitations of theory and experiment.

Experimental results show that the addition or removal of just one atom can markedly influence the activity, or rate of catalysis, and the selectivity, or ratio of desired to undesired

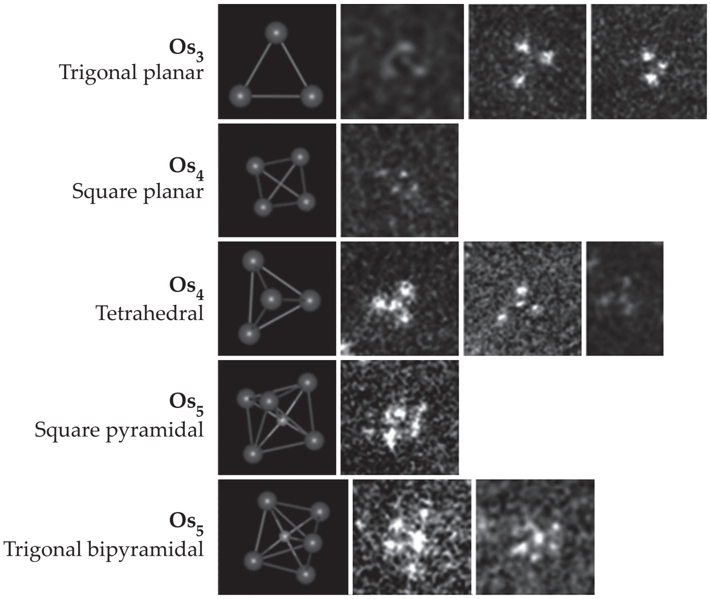


FIGURE 2. SCANNING TRANSMISSION ELECTRON MICROSCOPY IMAGES and crystallographic models (left) of three-, four-, and five-atom osmium clusters on magnesium oxide. (Adapted from ref. 3.)

products. For example, theory and experiment jointly showed[5] that Pt_7 dispersed on aluminum oxide is significantly more active for alkane dehydrogenation than Pt_8. Although the most stable forms of both supported Pt_7 and Pt_8 have three-dimensional morphologies with limited activities for dehydrogenation of alkanes, Pt_7 clusters have easy thermal access to metastable quasi-2D isomers that are significantly more active. Those active species actually do the catalysis. In contrast, the most stable 3D structure of Pt_8 clusters is dominant at all temperatures, and Pt_8 is overall less active. When supported on rutile (TiO_2), however, Pt_8 is a more active catalyst for CO oxidation than smaller platinum clusters.[6] Minor changes in cluster size, interactions with the support, and composition lead to major changes in catalytic properties, which open the door to catalyst tuning.

The support surface affects the nanoscale catalysts on it because most of the metal atoms are at the interface and interact with the surface underneath.[7] That interaction alters the morphology of the cluster, and it has a marked influence on the catalyst performance. Some supports, such as TiO_2, CeO_2, and other reducible oxides, tend to withdraw electrons from the metal, whereas some nonreducible oxides, including MgO and Al_2O_3, donate electrons. Although the magnitude of the charge transfer between the support and metal is usually small, it is sufficient to alter catalyst performance. Moreover, researchers can enhance the support's influence by preparing clusters nestled in support-surface defects such as metal or oxygen vacancies, which are common in oxides.

Fluxional and polymorphous

Until recently theorists working with metal clusters used simplified models that treated clusters as almost static entities. For a given size and composition, scientists determined the most stable structure, the ground state, and the chemical and catalytic properties only for that structure. Now theory compares the properties and structures of various isomers that are present during catalysis with similar energies but different catalytic

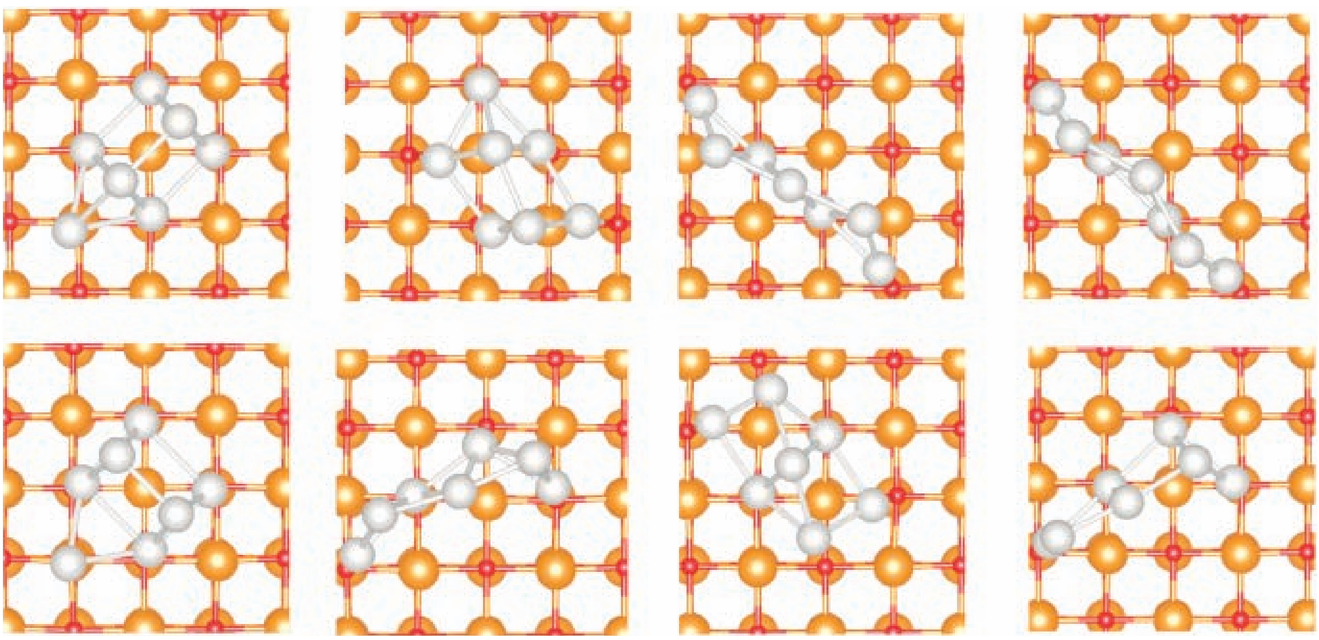


FIGURE 3. THE SEVEN-ATOM PLATINUM ISOMERS, shown from above, that are theoretically predicted to be energetically accessible on a perfect magnesium oxide (100) surface at 700 K. The isomers' different shapes and different bonding affinities influence their catalytic properties.

properties. Notably, the most stable isomer may not be the most catalytically active for the desired reaction.

Let us consider Pt_7 supported on a perfect MgO(100) surface. Figure 3 shows all the isomers that density functional theory (DFT) predicts to be energetically accessible at 700 K. Some of the structures have compact shapes, whereas others are extended along a line. Each one bonds differently to the support and thereby offers different sites with different affinities for bonding to the molecules involved in catalysis. However, computing the most stable geometries of a specific cluster is complicated, because a cluster's shape is not just a cut from the bulk. Thus the calculation requires a specialized method known as stochastic global optimization. In addition, some clusters, particularly those containing several metal atoms with incomplete populations of *d* orbitals, present a formidable challenge for DFT.

Theorists need better electronic-structure methods to overcome some of the limitations of DFT. For many structural forms of clusters, the problems average out, and the calculated structures qualitatively agree with experimental observations. But a main weakness of DFT is its inability to qualitatively capture the behavior of strongly correlated systems, such as manganese, iron, and cobalt oxides and sulfides.

Beyond the static structure, clusters convert from one isomer to another as the adsorbed molecules and reaction intermediates change over the course of a catalytic cycle. Structural changes are possible because the chemical bonds are delocalized and nondirectional in metal clusters. That dynamic structure, or fluxionality, is pronounced in catalytic processes because the temperatures are high, typically 700–800 K. The support also facilitates or hinders certain morphologies. But cluster fluxionality is not in reach of today's experimental capabilities. Researchers would need *operando* measurements capable of targeting one particular cluster on extremely short time scales and in complex environments. For now, theory and computation are leading the way toward understanding the fluxional character of the cluster catalysts.

One of our papers introduced new DFT-based algorithms that enabled investigations of the fluxional character, including the probability the shape will change and the time scales associated with those changes.[8] But the computational cost for a system of only seven Pt atoms and the support surface is still enormous. Extensions to more complex catalysts will require further improvements in computational capabilities and algorithm efficiency. Nonetheless, the available results already show that dozens of possible surface-supported Pt_7 isomers exist under the conditions of catalysis, as shown in figure 4. The most stable Pt_7 isomer is catalytically inactive, but the second most stable is highly active.

The number of thermally accessible isomers varies substantially and depends on the nature of the support, the number of atoms in the cluster, the cluster's stoichiometry, and its coverage with reactants, intermediates, and products. The complexity arises from the balance of forces from the intracluster elec-

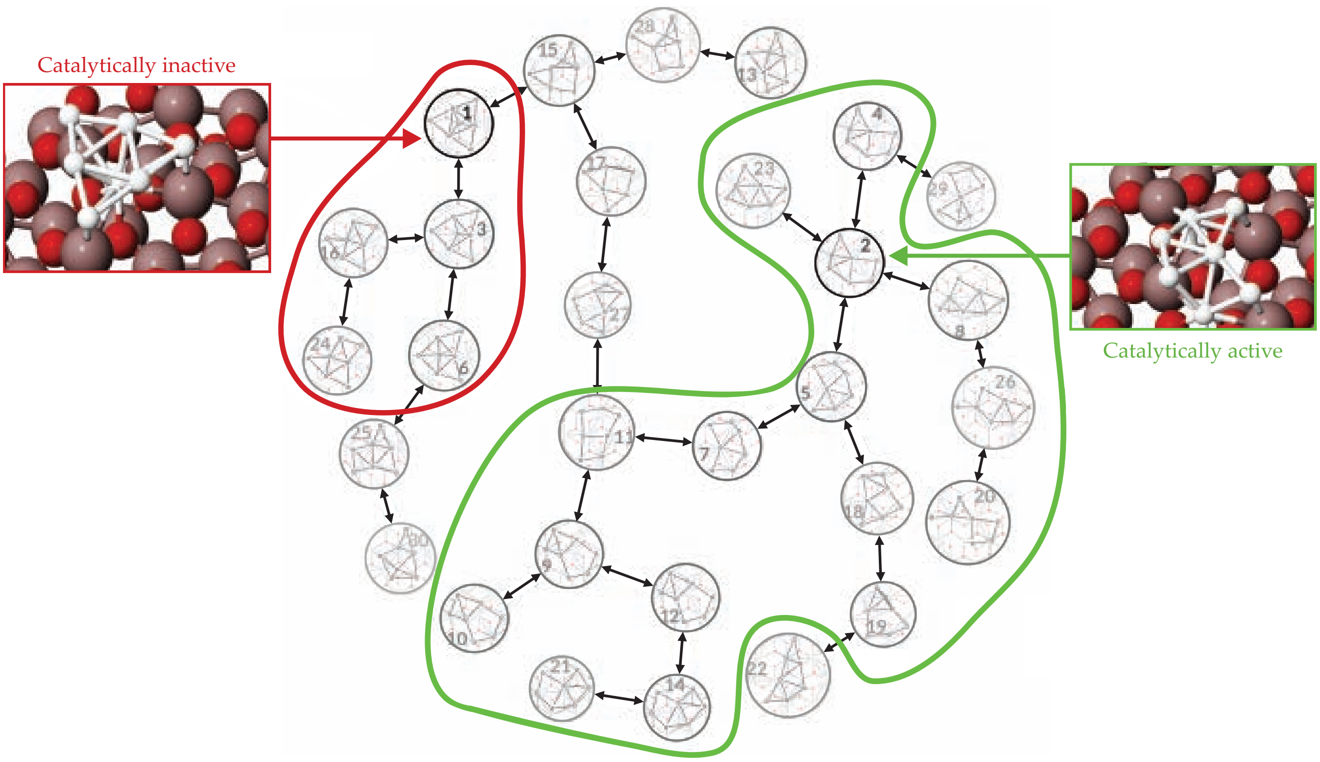


FIGURE 4. THE INTERCONVERSION OF SEVEN-ATOM PLATINUM ISOMERS on α-alumina indicates that the clusters are divided into two groups (circled in red and green). Within each group, the probability for cluster isomerization is high because energy barriers are low. But between groups, the probability is lower because the energy barriers are high. The most stable isomer (labeled as 1) belongs to the group circled in red, but that isomer is catalytically inactive. The second most stable isomer (labeled as 2) belongs to the second group (in green), and it is highly active catalytically. (Adapted from ref. 8.)

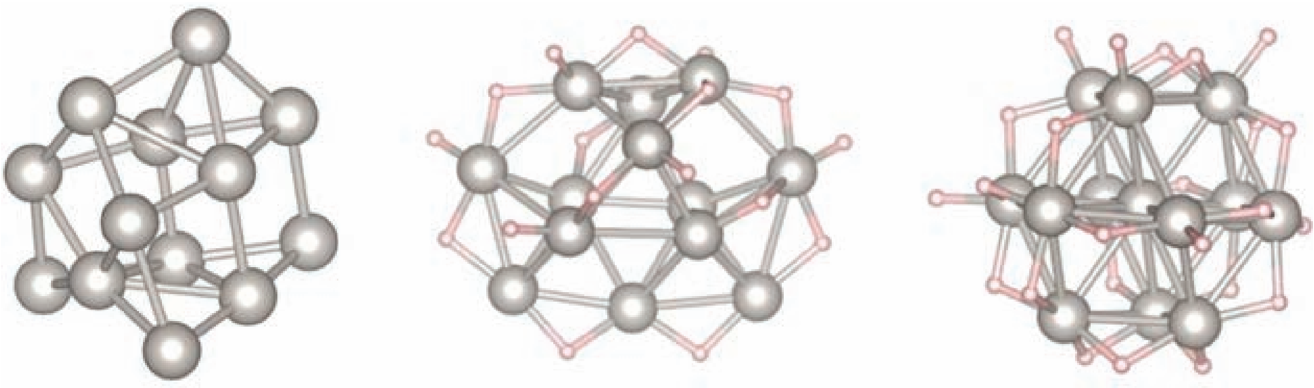


FIGURE 5. THE MOST STABLE 13-ATOM PLATINUM CLUSTERS WITH INCREASING ADSORBATES are shown for no hydrogen (left panel), 18 H atoms (center), and 26 H atoms (right). The cluster shape is transformed under the influence of a hydrogen atmosphere. (Adapted from ref. 11.)

tronic structure, cluster–support bonds, and cluster–molecule bonds. But that balance is not yet predictable. Only massive stochastic simulations can account for all of those effects.

Understanding the dynamics and fluxionality of supported clusters is a significant step forward, but that understanding alone can't predict the structures in practical catalysis without considering realistic conditions. In practice, the cluster shape depends on other aspects of the surrounding environment, including the structure of the supports, such as the nanopores of zeolites that envelop metal clusters, and the steady-state distribution of the bound reactants, intermediates, products, and impurities. Theorists still have a long way to go before real-world catalysts can be designed and understood from first principles.[9]

Interactions with adsorbates

One step toward realistic catalyst models is accounting for adsorbates on the clusters. They vary during a catalytic cycle—reactants on, intermediates formed, products off—and can dramatically modify the size and shape of cluster isomers.[10] For Pt_{13} clusters in an atmosphere of hydrogen, common in dehydrogenation catalysis, Geng Sun and Philippe Sautet of UCLA used a simplified model that ignored the influence of the support, because high coverage of hydrogen causes the particle to become globular and lose some interactions with the support. They found that the adsorbate exerts a marked effect on the Pt_{13} cluster morphology.[11]

Without adsorbates, many isomers are energetically accessible at high temperatures. Using methods similar to those for Pt_7 clusters, Sun and Sautet predict that the most stable geometry of Pt_{13} is a tricapped pentagonal prism, shown in the left panel of figure 5. With the addition of 18 hydrogen atoms, the most stable structure has a geometry resembling a seashell, as in the center of figure 5, and the number of isomers is reduced from 49 for Pt_{13} to 20 for $Pt_{13}H_{18}$. Additional hydrogen atoms (up to 26), change the number of populated isomers only slightly, but the isomers have different shapes, as seen in the right panel of figure 5, and thus different binding sites and reactivities. The enhanced ability of certain cluster morphologies to adsorb hydrogen may drive the structural transformations. Could nanoclusters' adaptability contribute to their outstanding catalytic performance? Are they smart catalysts? Much more work is needed.

The daunting complexity of real catalysis

Real supported metal cluster catalysts are complex mixtures, with their properties influenced by the cluster size, the support, and the adsorbates, all of which influence cluster morphology. Accurate predictions of the catalytic properties would require a tour de force of modeling or incisive *operando* characterization by imaging and spectroscopy, both far beyond our current capabilities.

Theoretical demonstrations show that clusters' electronic structures, morphologies, and interactions with supports strongly influence catalytic performance and that cluster fluxionality is important. Those results help experimentalists realize the limitations of data that characterize catalysts that are not in the working state; they also show the importance of developing high-speed imaging techniques that are orders of magnitude faster than today's capabilities to capture rapid morphological changes, which occur in tens of picoseconds. The insights emerging from both theoretical and experimental research are beginning to guide practical catalyst discovery—for example, by focusing development on small clusters, clusters that are stabilized by their interactions with supports, and supports that optimize those interactions.

REFERENCES

1. M. Haruta et al., *Chem. Lett.* **16**, 405 (1987).
2. Z. Xu et al., *Nature* **372**, 346 (1994).
3. C. Aydin et al., *Angew. Chem. Int. Ed.* **52**, 5262 (2013).
4. A. Kulkarni et al., *Angew. Chem. Int. Ed.* **49**, 10089 (2010).
5. E. T. Baxter et al., *ACS Catal.* **7**, 3322 (2017).
6. Y. Watanabe et al., *Catal. Sci. Technol.* **1**, 1490 (2011).
7. A. Kulkarni, R. J. Lobo-Lapidus, B. C. Gates, *Chem. Commun.* **46**, 5997 (2010).
8. H. Zhai, A. N. Alexandrova, *J. Phys. Chem. Lett.* **9**, 1696 (2018).
9. E. Jimenez-Izal, A. N. Alexandrova, *Annu. Rev. Phys. Chem.* **69**, 377 (2018).
10. A. M. Argo et al., *Nature* **415**, 623 (2002).
11. G. Sun, P. Sautet, *J. Am. Chem. Soc.* **140**, 2812 (2018).

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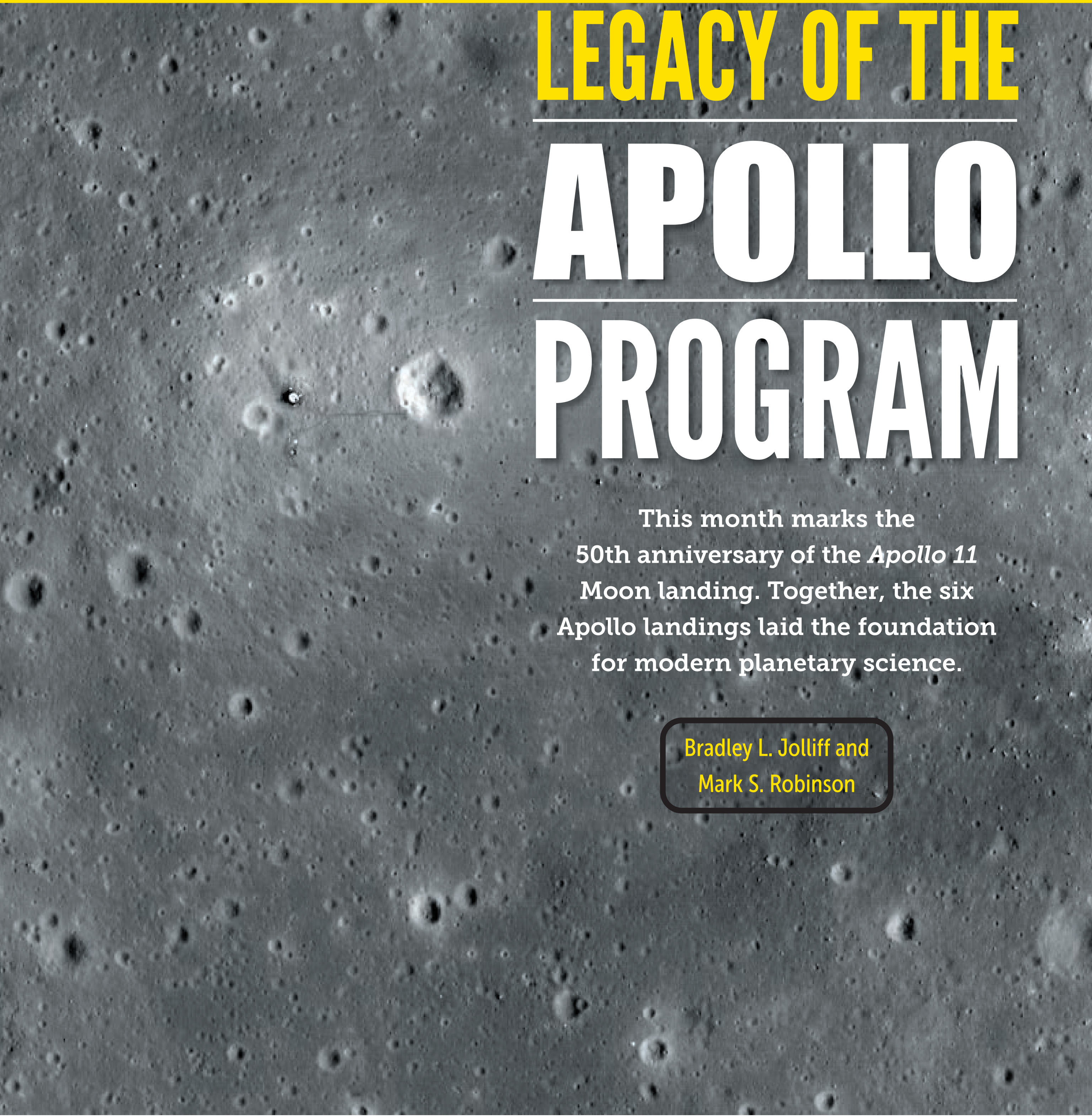
THE SCIENTIFIC LEGACY OF THE APOLLO PROGRAM



This month marks the 50th anniversary of the *Apollo 11* Moon landing. Together, the six Apollo landings laid the foundation for modern planetary science.

Bradley L. Jolliff and Mark S. Robinson

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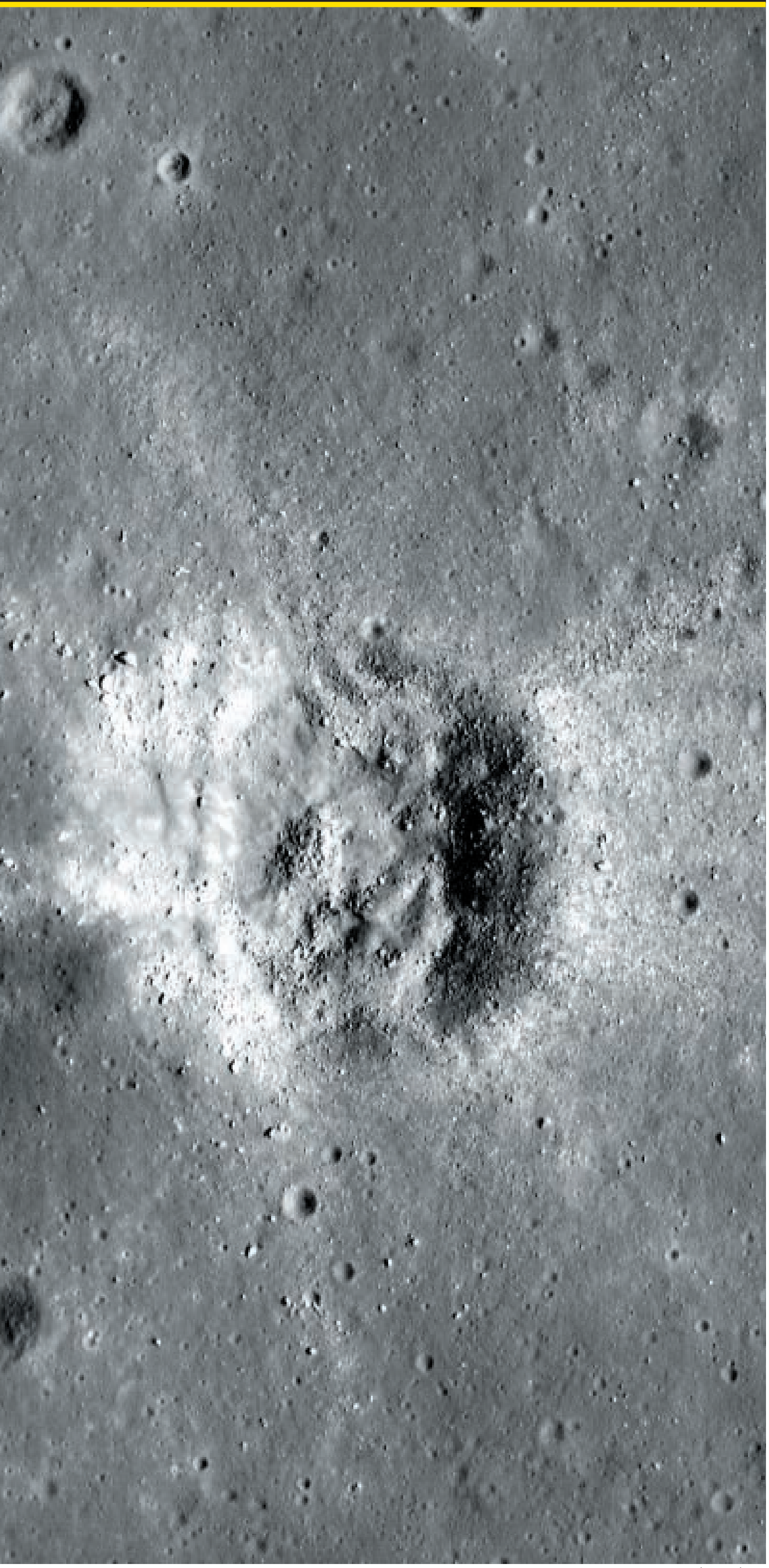


NASA/GSFC/ASU

On 20 July 1969, *Apollo 11* astronauts Neil Armstrong and Edwin "Buzz" Aldrin landed on the Moon while Michael Collins orbited in the command module *Columbia*. "Tranquility Base here. The *Eagle* has landed" became one of the most iconic statements of the Apollo experience and set the stage for five additional Apollo landings.

Each of the Apollo missions explored carefully selected landing sites and conducted a variety of experiments to probe the lunar interior and measure the solar wind. Well-trained astronauts made geologic observations and collected samples of rock and regolith, the impact-generated layer of debris that composes the lunar surface. Over a half century of study, the samples have revealed abundant information not only about the Moon's origin and history but also about the workings of our solar system.

Apollo 11

Results from the *Apollo 11* mission established key paradigms of lunar and planetary science. After a harrowing descent to the surface, Armstrong set the *Eagle* down on the cratered basaltic plains of *Mare Tranquillitatis*. Extravehicular activity was brief—just two and a half hours during that first mission—and included setting up surface experiments and exploring a small cluster of craters near the lunar module and Little West Crater some 60 meters away, as shown in figure 1. Aldrin's iconic *Apollo 11* bootprint photo revealed much about the lunar soil, including its fine-grained nature, its cohesiveness, and its ability to pack tightly together.

The Early Apollo Scientific Experiment Package contained, among other instruments, a passive seismometer and a laser-ranging retroreflector. Although designed to work for only three weeks, the seismometer provided a first key look at lunar seismic data. The seismometers brought to the Moon during the *Apollo 12*, *14*, *15*, and *16* missions were used as a larger network to probe the interior structure and measure thousands of moonquakes that would eventually be detected.

The retroreflector on *Apollo 11* was the first of five eventually delivered to the Moon. Active laser ranging still precisely measures the Moon's distance as it slowly recedes from Earth. Some 22 kg of samples were collected during that mission. (Collectively, the missions returned a total of 382 kg of material, and the last, *Apollo 17*, carried 111 kg.) The regolith, used as filler in the rock box, was separated from the rocks back on Earth and analyzed for its contents. The fine-grained particles, labeled 10084 and known as "Armstrong's packing soil," may be the most studied geologic sample in history.

The rocks turned out to be largely basalt—volcanic rock formed by partial melting in a planet's (or moon's) interior. They contained higher concentrations of titanium than any basalts on Earth but were otherwise made of familiar minerals, primarily the Mg-Fe-Ca silicate mineral pyroxene, the Ca-Al silicate mineral plagioclase, and the Fe-Ti oxide ilmenite.

Radiometric dating found the basalts to be more than 3.5 billion years old, and isotopic relationships between rock and regolith materials suggested that the Moon itself is ancient, having formed earlier than 4.4 billion years ago.[1] Although the volcanic rocks contain vesicles, indicative of gas release upon eruption, they lack evidence of any other alteration and are nearly devoid of water, carbon dioxide, and other volatiles. (See the Quick Study by Lindy Elkins-Tanton, PHYSICS TODAY, March 2011, page 74.) Lunar rocks are also completely barren of any signs of life.

The regolith samples proved invaluable in the rich variety of materials contained within them (see, for example, figure 2). Meteor and asteroid impacts, pervasive in lunar history, ejected bits of rock tens to hundreds of kilometers in all directions. Volcanic glasses, impact glasses, and breccias—rock fragments that became mixed during those impacts—were all part of the regolith. So were agglutinates, a new type of welded soil particle produced by micrometeorite impacts in the regolith. Mixed in with that local material were small fragments of plagioclase-rich rock (anorthosite) from the distant highlands.

In 1970 geologist John Wood and others inferred that anorthosite crystals floated toward the surface of a magma ocean, where they accumulated to form a plagioclase-rich crust.[2] Denser minerals such as pyroxene and olivine, by contrast, sank to form the lunar mantle. The Moon thus formed hot and underwent differentiation early in its history. (See PHYSICS TODAY, February 2008, page 16, and the article by Dave Stevenson, November 2014, page 32.) That early history was unraveled from only a handful of small rock fragments found in the regolith.

Building on success

Apollo 12 followed quickly in November 1969. The lunar module *Intrepid* executed a pinpoint landing within walking distance of the pre-Apollo *Surveyor 3* spacecraft. The landing site afforded the possibility of sampling not only local rocks and regolith but also materials ejected from Copernicus Crater, 350 km away. Part of *Apollo 12*'s payload included a seismometer, magnetometer, solar-wind spectrometer, and ion and dust detectors—all powered by a radioisotope thermoelectric generator. In addition to taking hardware from *Surveyor 3* for the trip back to Earth, the astronauts explored several craters and collected material excavated from different depths to establish a stratigraphy of the subsurface.

Besides several types of basalts, the astronauts sampled rocks that were likely part of a spoke-like ray of material ejected from Copernicus Crater. Among the materials were ropy glasses and nonbasaltic rocks, which offered evidence that the crater had formed 800 million years ago.[3] The inferred age of Copernicus Crater and subsequent dating of other impact craters and volcanic surfaces became the foundation for lunar chronology. The ground-truth data allow us to relate the size and frequency of impact craters per unit area to the age of the surface under study (see figure 3). And that relationship forms the basis for the relative chronologies of impact and volcanic events on the solar system's other rocky planets—Mercury, Venus, and Mars.[4]

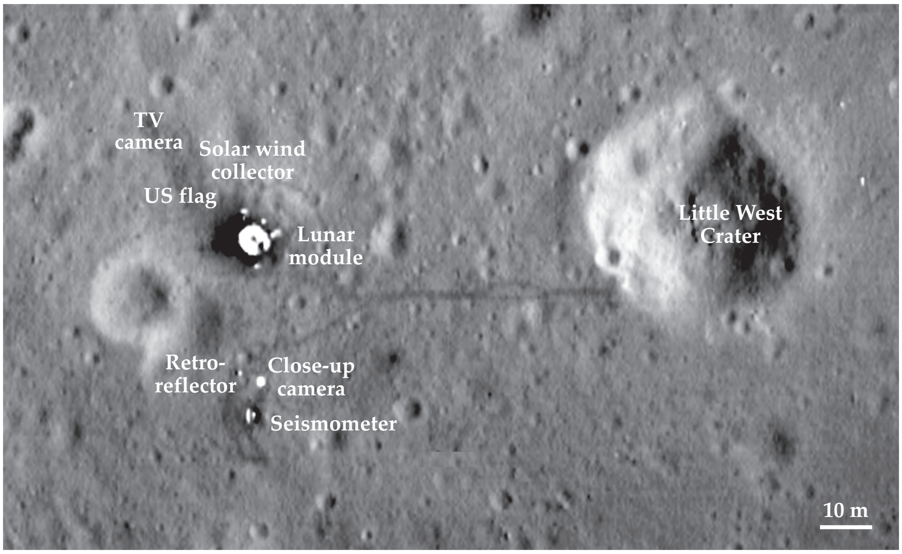


FIGURE 1. THE *APOLLO 11* LANDING SITE shows locations where a US flag, television camera, and surface experiments were placed by astronauts Neil Armstrong and Edwin "Buzz" Aldrin. As they placed instruments and walked around the landing site, the disturbed soil left a visible path. (Image courtesy of NASA/GSFC/ASU.)

The *Apollo 12* samples proved remarkably diverse. The material known as KREEP—rich in potassium, rare-earth elements, and phosphorus—was found in impact-melt rocks and rare granites. Several types of basalt, distinct from those found at the *Apollo 11* landing site, came from the underlying sequence of lava flows.

The *Apollo 14* lunar module *Antares* was the first to land on terrain that differed from flat volcanic plains. Analysis of orbital photos of the location, known as the Fra Mauro formation, indicates that the rocks there came from the enormous Imbrium basin-forming impact event, which occurred more than 600 km to the north. Fra Mauro breccias were determined to have

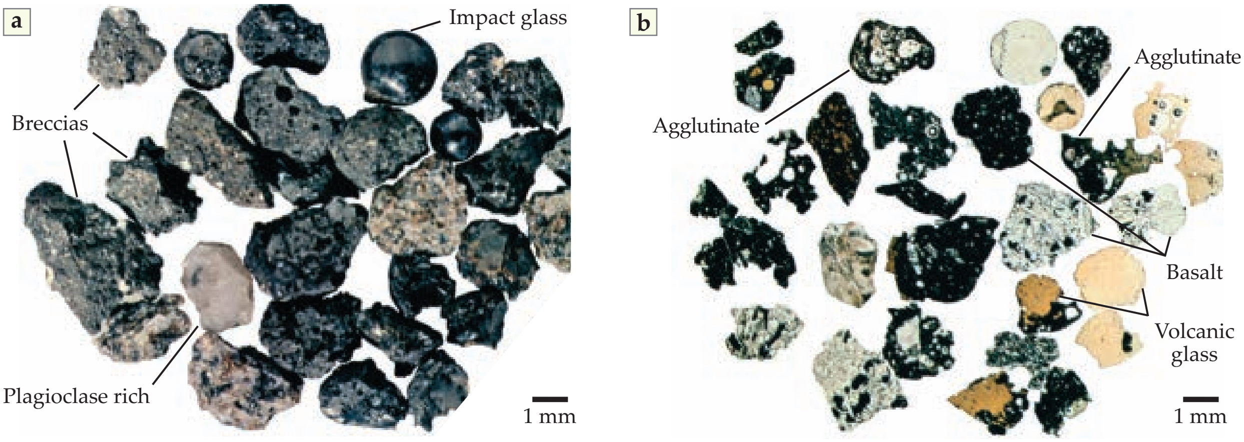


FIGURE 2. SOIL PARTICLES FOUND IN THE MOON'S SURFACE DEBRIS, or regolith, during the *Apollo 11* mission. **(a)** Shown here are rock fragments (impact breccias); volcanic and impact glasses; fused particles (agglutinates); a light-colored, plagioclase-rich fragment; and pieces of volcanic basalt. **(b)** The same rock particles are sliced optically thin for study by transmitted-light microscopy. (Images are from John Wood, Smithsonian Astrophysical Observatory.)

formed about 3.9 billion years ago. Because Imbrium is known from relative stratigraphy to be one of the youngest of the impact basins, almost all the other basins must have formed before that time. Excavated from deep in the lunar crust, the Imbrium rocks are rich in KREEP.[5] Exposure ages of samples ejected from the nearby Cone Crater revealed the crater to be 50 million years old, providing another key datum in lunar chronology.[6]

Apollo 15 and *16*

Launched in the summer of 1971, *Apollo 15* was the first of the so-called J missions, which included the first lunar rover and longer extravehicular activity—nearly 19 hours on the lunar surface—during which astronauts collected some 77 kg of samples and explored more complex geology. The lunar module *Falcon* landed on another flat mare deposit close to the spectacular Apennine mountains. Some peaks rise up to 4000 m above the landing site and are part of the rim of the Imbrium basin. A key mission goal was for the astronauts to traverse the base of Mons Hadley Delta, one of the Apennine peaks, to search for ancient crustal material brought up from the depths when the basin was formed.

One of the most remarkable finds was a clod of green pyroclastic glass beads, which represented material from deep in the mantle brought up rapidly, without crystallizing, to the surface during the eruption of a massive fire fountain. Perhaps the most famous of the samples whose collection was enabled by the rover was "Seatbelt Rock," a highly vesicular basalt shown in figure 4 and discovered by mission commander David Scott. Knowing that the astronauts were short on time and that mission control would not approve a stop to collect the rock, Scott used the excuse of stopping to fasten his seatbelt—hence the name—during which he quickly picked it up.[7]

Trained to look for coarsely crystalline rocks that might represent deep crustal material, Scott and others recognized the importance of yet another sample, "Genesis Rock," by its light color and coarse, reflective crystal facets. The rock proved to be anorthosite, considered a plagioclase flotation cumulate of the magma ocean and thus a pristine sample of lunar crust. Isotopic analyses confirmed that the rock is indeed ancient—more than 4 billion years old. But analyses also revealed a complex thermal and shock history that obscures when it actually formed. Collection and documentation of the rocks in their geologic contexts, along with precise locations and descriptions by the astronauts, enabled the construction of exquisitely detailed maps and cross sections of the landing sites.[8]

Another advance with the J missions was addition of the Scientific Instrument Module (SIM) on the *Endeavor*. It enabled systematic orbital remote sensing using panoramic and mapping cameras; x-ray and gamma-ray spectrometers, which determined elemental compositions; and a laser altimeter for topography. SIM bay observations by the *Apollo 15*, *16*, and *17* missions provided an approximately equatorial swath of data for the lunar surface that researchers used to extrapolate from "Apollo-zone" areas to the entire Moon. The J-mission orbital observations had to last the scientific community until the 1990s, when the *Clementine* and *Lunar Prospector* spacecraft acquired global remote sensing.

Apollo 16 was the only mission that explored lunar highlands far from the maria. The lunar module *Orion* gently landed near mountainous terrain known as the Descartes highlands. The main scientific goal was to investigate the origin of the Cayley plains, a region adjacent to those highlands and thought, prior to the mission, to have formed from silica-rich rocks and ash deposits. The Cayley plains actually overlap the mountainous Descartes formation and are thus younger. From orbital photography, geologists interpreted the Descartes formation as ejecta from the ancient Nectaris basin, whose rim is less than 300 km away.

Apollo 16 astronauts took advantage of the sampling opportunities afforded by two impact craters, North Ray and South Ray, by landing between them. Using the rover, they sampled ejecta from both to determine their ages—yet more data points for the lunar chronology. The relatively smooth Cayley plains were shown to have formed as an impact-related deposit, most likely by material ejected from Imbrium. Among the rocks ejected from North Ray and South Ray Craters were impact-melt, fragmental, and regolith breccias. The latter, composed of lithified regolith, were significant because they provide a time-stamped snapshot of the output of the Sun via trapped solar-wind gases at the time the regolith breccias formed.

The largest Apollo sample ever returned was a 12 kg breccia nicknamed "Big Muley," after Bill Muehlberger, who led the *Apollo 16* and *17* field geology teams. The side of the rock that faced up on the lunar surface is dotted with an abundance of pits from its exposure to micrometeorites. An important legacy of the Apollo missions is the superb training that was incorporated into the program. That training allowed the astronauts to work directly with scientists at mission control to optimize the fieldwork. The approach culminated with the inclusion on *Apollo 17* of a geologist astronaut, Harrison Schmitt.

Peaks and valleys

Apollo 17 landed in the beautiful Taurus–Littrow Valley, completing the Apollo program in December 1972. The lunar module *Challenger* placed the astronauts in a geologically complex area on the edge of the Serenitatis basin. The valley itself is defined by peaks, shown in figure 5, that tower 2500 meters above the basalt-flooded floor. Mission objectives included ascertaining the age of the basin, determining the age and composition of the basalts, and collecting pieces of ancient crust excavated during the basin's formation.

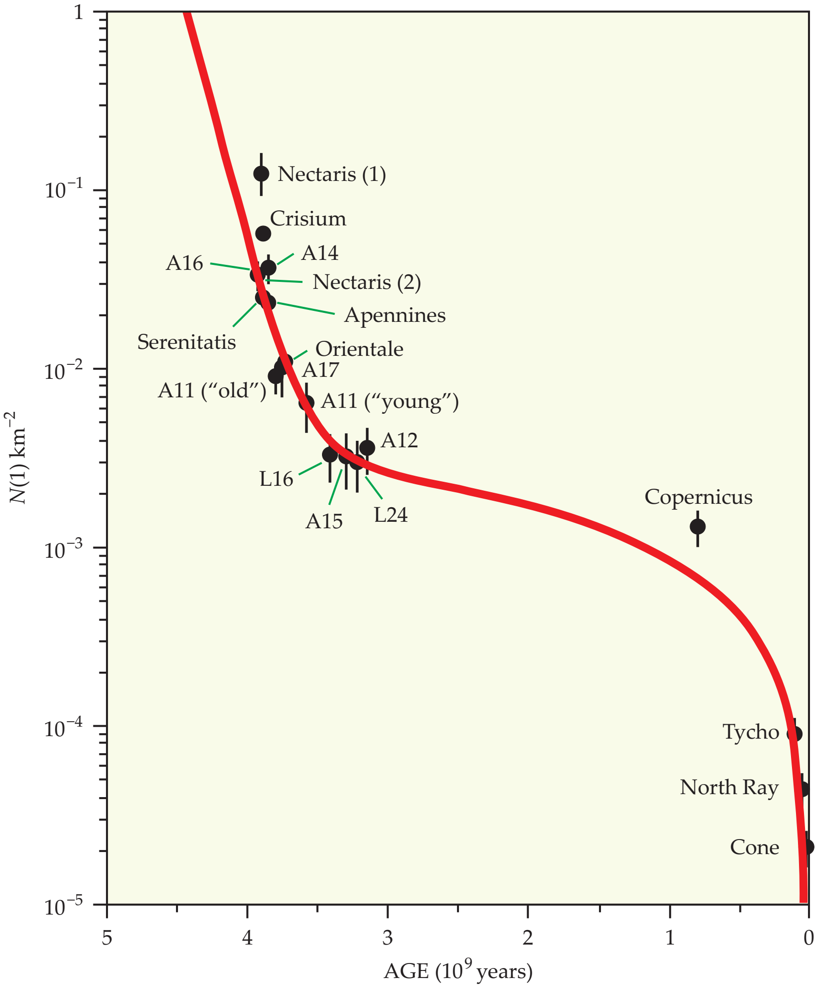


FIGURE 3. LUNAR CHRONOLOGY is based on the ages of lunar samples that represent surfaces on which impact crater size–frequency distributions have been determined. *N*(1) refers to the number of craters that are 1 km in diameter or larger, and the plot relates that number to the crater accumulation time. Numbered labels "A" and "L" refer to Apollo and Luna missions, respectively. Measurements of crater size and frequency distributions come from orbital photographs. (The method and plot are adapted from ref. 4; the age data are taken from ref. 5.)

Mission planners had identified a large, regional pyroclastic ash deposit in orbital images and wanted to find and sample some of that material. A cluster of secondary impact craters, aligned along a ray from the 2400-km-distant Tycho Crater, was seen in the valley along with a light mantle deposit, formed by avalanche, at the base of South Massif. Scientists hypothesized that the craters and the mantle deposit formed as ejecta from Tycho Crater struck the area. Astronauts sampled the light mantle deposit for researchers to determine Tycho's age, as had been done for Copernicus Crater during the *Apollo 12* mission.

Additionally, Schmitt discovered a deposit of orange glass beads as an exposed layer in the rim of Shorty Crater. That material was pyroclastic as well. The color was related to their high Ti content, quite different from the very low Ti of the *Apollo 15* green glasses. Like the green glass, however, the orange-glass soil became one of the most important of the Apollo samples, oft sought for study because it represents one of the most pristine samples of the lunar interior, unmodified by crystallization processes.

Basalts of the Taurus–Littrow Valley formed 3.7–3.8 billion years ago. Impact-melt breccias were sampled from boulders at the base of North and South Massifs, their ages just a few tens of millions of years older than the breccias from Imbrium. Because of the considerably more advanced degradation of Serenitatis basin, it was apparent that many impact basins had formed in that time interval, amounting to a cataclysmic bombardment as also suggested by lead-isotopic analyses.[9] Samples collected on the light mantle deposit and elsewhere in the valley had exposure ages of around 110 million years, and that age was assigned to the Tycho impact event.[10] Ancient crustal rocks greater than 4.0 billion years old were also found among the *Apollo 17* samples. They continue to provide the grist for tests of hypotheses about the origin of the Moon's ancient crust.

Unlike its predecessors, *Apollo 17* carried an active seismic experiment designed to determine the subsurface structure by picking up signals generated by explosive charges. Other experiments probed surface electrical properties, determined the effects of exposure of biological materials to cosmic rays, and used a traverse gravimeter to help map out subsurface structure. The orbiting command service module *America* carried a microwave sounder, an IR radiometer, a far-UV spectrometer, mapping and panoramic cameras, and a laser altimeter. The orbital data sets provided by those instruments would be the last

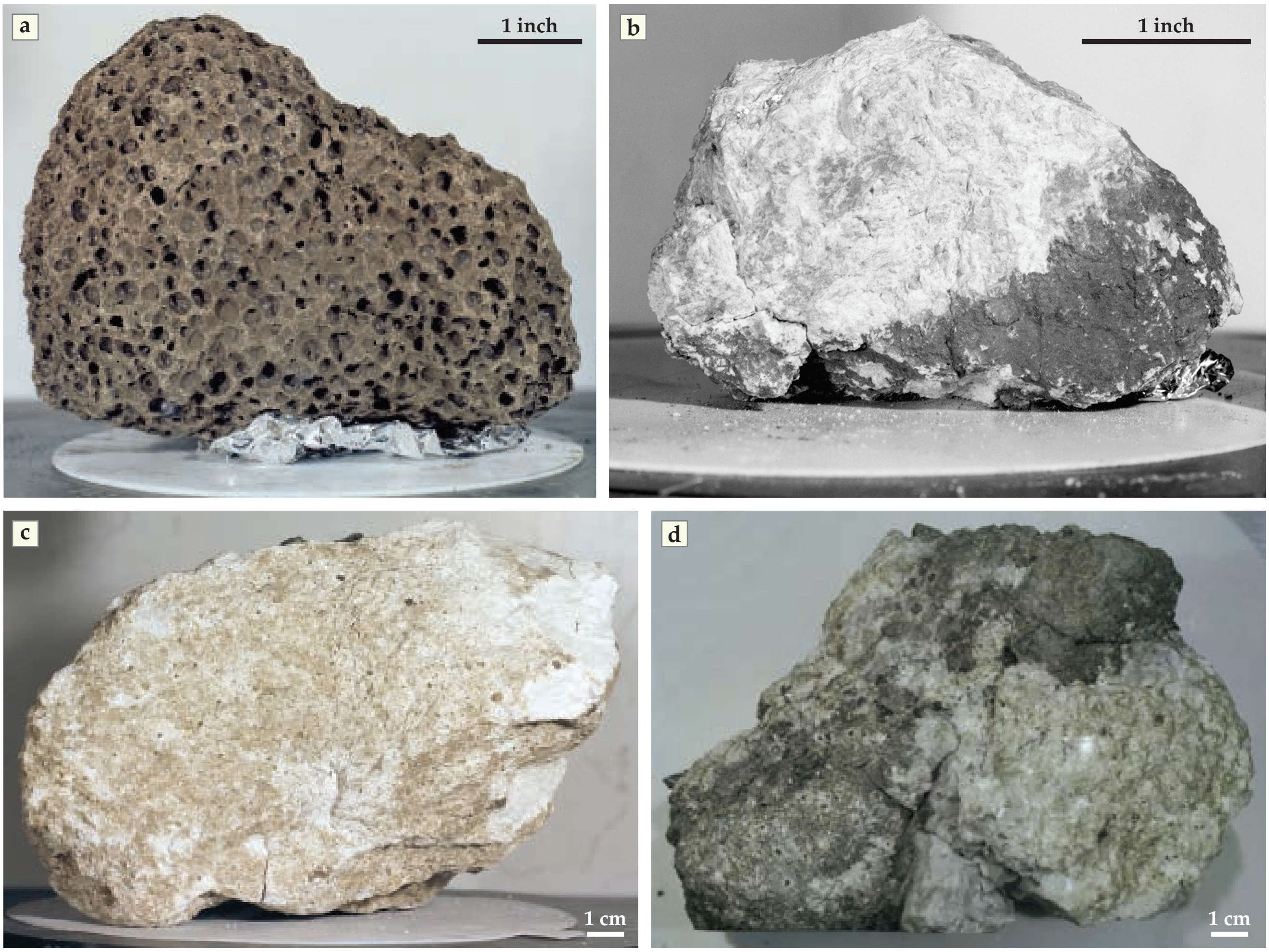


FIGURE 4. ROCKS COLLECTED during *Apollo 15* and *Apollo 16*. **(a)** "Seatbelt Rock" 15016 is a vesicular (porous) basalt. (Adapted from NASA photo S71-46632.) **(b)** "Genesis Rock" 15415 is made of ferroan anorthosite, a major rock type of the lunar crust. (Adapted from NASA photo S71-44990.) **(c)** A 1.8 kg sample of anorthosite, 60025. (Adapted from NASA photo S72-42586.) **(d)** This top surface of an 11.7 kg breccia, 61016, known as "Big Muley," contains numerous tiny impact craters, or zap pits. (Adapted from NASA photo S98-01215.)

direct measurements scientists would have from lunar orbit for more than two decades.

Surface geophysics

The seismic array deployed by *Apollo 12*, *14*, *15*, and *16* continued to transmit data to Earth until September 1977, when the array and other instruments were turned off. More than 12 000 seismic events were detected altogether. Some 7000 of them came from deep moonquakes, which were correlated with tidal forces exerted by Earth's gravity. Others were attributable to meteoroid impacts, the deliberate crashes of booster rockets, and shallow thermal moonquakes caused by the heating and expansion of the crust.

Seismic data provided information about the thickness of the lunar crust, changes in the seismic velocity as waves crossed the crust–mantle boundary, deeper seismic discontinuities in the mantle, and a deep zone of seismic attenuation. Early work estimated the average crustal thickness at 60 km, but modern analyses place it between 30 and 40 km.[11,12]

Ranging to the lunar retroreflectors from Earth continues today. The Moon's irregular rotational motions indicate a partially fluid core. The 2011 Gravity Recovery and Interior Laboratory (GRAIL) mission confirmed a partially molten deep-mantle zone and constrained the size of the fluid outer and solid inner core.[13] (See PHYSICS TODAY, January 2014, page 14.) Coupled with the available Apollo seismic data, the new gravity measurements significantly improve our understanding of the Moon's internal structure.

Samples and curation

The Apollo samples are broadly similar to Earth materials in mineralogy and chemical composition. But their chemistry is distinctly lunar. Moon rocks formed under extremely low oxygen fugacity such that most of the iron they contain is divalent (Fe^{+2}) and most samples contain at least a small amount of iron metal (Fe^0). The Fe-Ti oxides are mostly ilmenite ($FeTiO_3$), but also contain ulvöspinel (Fe_2TiO_4), armalcolite ($(Fe,Mg)Ti_2O_5$) (first found in lunar rocks and named after *Arm*strong, *Al*drin, and *Col*lins), and tranquillityite ($Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$), a new mineral named for the Sea of Tranquillity, where it was found.

The basalts provide insights into the lunar mantle and early differentiation processes. Variations in basalt types reflect a heterogeneous mantle, which lacks a homogenizing process such as Earthlike convection. Owing to ground-truth samples from Apollo, we can infer basalt types from other areas using remote sensing. Volcanic glasses occur in regolith samples from all Apollo sites, with a wide variety of compositions, spanning TiO_2 concentrations from less than 1 weight percent to more

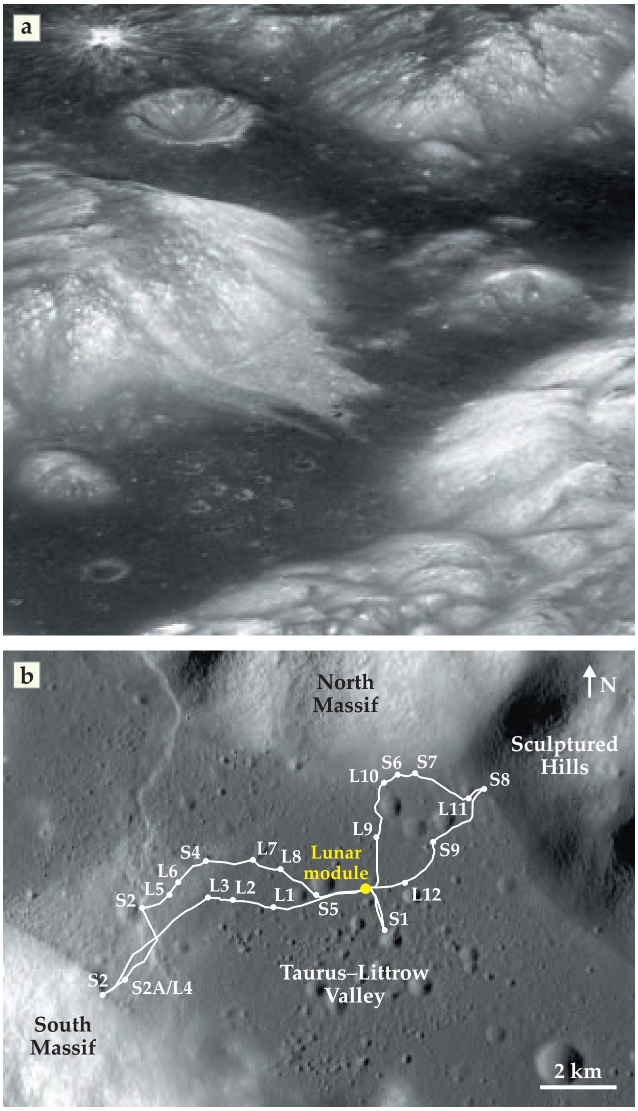


FIGURE 5. TAURUS–LITTROW VALLEY, the landing site for *Apollo 17*. **(a)** In this oblique, 18-km-wide scene looking generally to the west, *Mare Serenitatis* is at the upper right. North is to the right. (Image courtesy of NASA/GSFC/ASU.) **(b)** This view of the valley (the lower left part of panel a) shows the astronaut traverses. Numbered labels "S" and "L" refer to sampling stations and lunar-roving-vehicle stops, respectively. (Image courtesy of NASA/GSFC/ASU.)

than 16 weight percent. Those compositions reflect the heterogeneity of the mantle and late-stage magma-ocean processes that led to areas within the mantle of widely different Ti contents.

During the Apollo program, scientists had the foresight to recognize the value of the samples and established the Curatorial Facility at Johnson Space Center. They set protocols for curation, handling, and allocation in a way that would preserve portions of all samples for future generations, with special care given to the rarest and most important of them.

The protocols ensured that nearly 40 years after they were collected, samples would be available for analysis of indigenous OH and H_2O in volcanic glasses, phosphate minerals, and melt inclusions using new and highly sensitive analytical methods. Those studies revealed that the Moon did not form as depleted of volatiles as was once thought.[14–16] (See also PHYSICS TODAY, January 2016, page 17.) Rather, the Moon heavily degassed the volatiles during the magma-ocean and later volcanic stages. The precise measurement of remanent magnetism in lunar samples revealed that the Moon had an early core dynamo until sometime between 3 billion and 4 billion years ago (reference 17; see also the article by David Dunlop, PHYSICS TODAY, June 2012, page 31).

Gateway to the solar system

The Apollo era exploration and decades of study of lunar samples laid a foundation of knowledge about Earth's nearest neighbor and provided a cornerstone for planetary science. Apollo showed the Moon to be ancient, some 4.5 billion years old and made of materials similar to those on Earth, but consistent with the Moon's smaller size, lower pressure, lack of atmosphere, and lack of any obvious aqueous alteration. Its minerals and rocks bore evidence of an early magma ocean and differentiation into a mantle and crust. Heating and remelting of the interior produced voluminous basaltic volcanism 3-4 billion years ago. From study of Apollo samples and data came the concept of the Moon's formation via a giant impact on early Earth, which still stands as the leading hypothesis for the origin of the Moon. Apollo surface samples gave us our first look at alteration by exposure to galactic cosmic rays, energetic solar particles, and meteorites, ranging from microscopic to asteroidal.

Perhaps the most far-reaching scientific legacy of Apollo is the ongoing exploration of our solar system. The Apollo samples provided the first evidence of the so-called late, heavy bombardment of asteroids, thought to have spiked around 3.9-4.0 billion years ago. Models of the early solar system's orbital dynamics suggest that shifts in the orbits of Jupiter and Saturn may have destabilized early asteroid and cometary belts and led to that cataclysm some 500 million years after the solar system formed.[18]

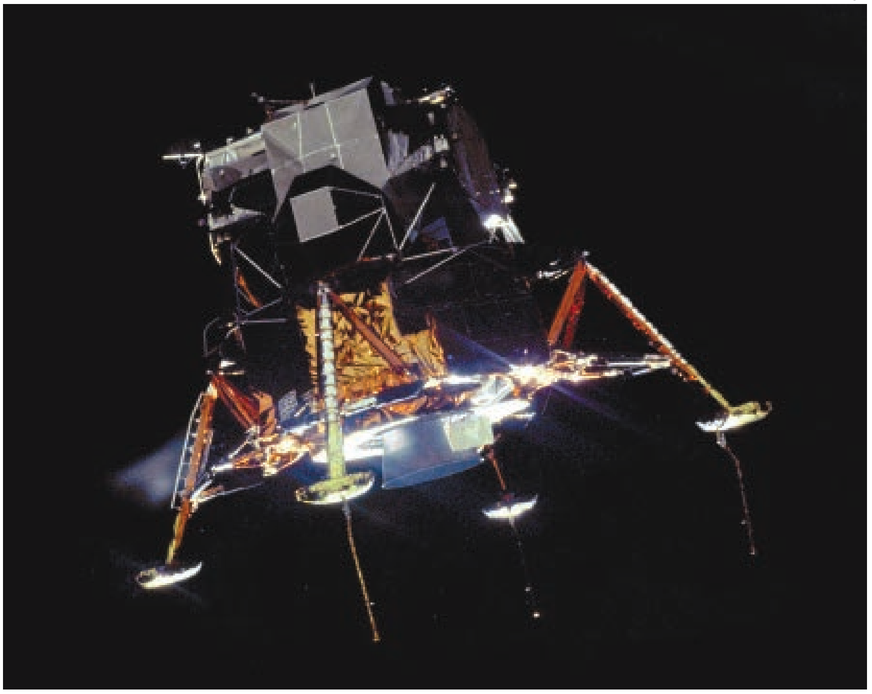
The Apollo samples and explorations showed that the key to testing those dynamical models is on the Moon, awaiting the next round of surface exploration and sample collection.

REFERENCES

1. D. A. Papanastassiou, G. J. Wasserburg, D. S. Burnett, *Earth Planet. Sci. Lett.* **8**, 1 (1970).
2. J. A. Wood et al., in *Proceedings of the Apollo 11 Lunar Science Conference*, A. A. Levinson, ed., Pergamon Press (1970), p. 965.
3. P. Eberhardt et al., *Moon* **8** 104 (1973).
4. G. Neukum, B. A. Ivanov, W. K. Hartmann, *Space Sci. Rev.* **96**, 55 (2001).
5. P. H. Warren, J. T. Wasson, *Rev. Geophys.* **17**, 73 (1979).
6. D. Stöffler, G. Ryder, *Space Sci. Rev.* **96**, 9 (2001).
7. D. E. Wilhelms, *To a Rocky Moon: A Geologist's History of Lunar Exploration*, U. Arizona Press (1993).
8. P. Spudis, C. Pieters, in *Lunar Sourcebook: A User's Guide to the Moon*, G. H. Heiken, D. T. Vaniman, B. M. French, eds., Cambridge U. Press (1991), chap. 10.
9. F. Tera, D. A. Papanastassiou, G. J. Wasserburg, in *Fifth Lunar Science Conference*, Lunar Science Institute (1974), p. 792.
10. R. J. Drozd et al., in *Eighth Lunar Science Conference*, Lunar Science Institute (1977), p. 254.
11. A. Khan, K. Mosegaard, *J. Geophys. Res. Planets* (2002), doi:10.1029/2001JE001658.
12. P. Lognonné et al., *Earth Planet. Sci. Lett.* **211**, 27 (2003).
13. J. G. Williams et al., *J. Geophys. Res. Planets* **106**, 27 933 (2001).
14. A. E. Saal et al., *Nature* **454**, 192 (2008).
15. F. M. McCubbin et al., *Am. Mineral.* **95**, 1141 (2010).
16. E. Hauri et al., *Science* **333**, 213 (2011).
17. B. P. Weiss, S. M. Tikoo, *Science* **346**, 1198 (2014).
18. R. Gomes et al., *Nature* **435**, 466 (2005).

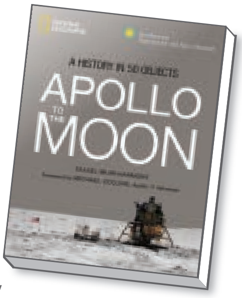
PT

NASA



Curating the lunar landing

Apollo to the Moon
A History in 50 Objects
Teasel Muir-Harmony
Smithsonian Institution and National Geographic, 2018. $35.00



A plethora of books are being released in 2019 to celebrate the 50th anniversary of the Moon landing, arguably the greatest technical achievement in human history. *Apollo to the Moon: A History in 50 Objects* deserves to be noticed even among that crowded field. This remarkable book by Teasel Muir-Harmony, a curator at the Smithsonian National Air and Space Museum, tells the story of the technical and human aspects of the Apollo program through a series of objects.

To accomplish that feat, Muir-Harmony uses both her own expertise and a few contributions from noted Apollo scholars. She also includes sections written by two key players in the first steps on our nearest neighbor. From the forward by Michael Collins, command module pilot on *Apollo 11*, to the closing comments of Buzz Aldrin, the lunar module pilot on the same mission, readers are in for a stunning ride through the familiar and the surprising.

Collins's forward is especially notable, since he acted as director of the Smithsonian National Air and Space Museum from 1972 to 1978. He was not only a part of the history-making event of *Apollo 11*, but he has a unique perspective on object curation and oversight. His forward adds gravitas to an engaging and significant book.

What will strike any reader who has a passion for the history of Apollo is the level of detail the author incorporates. The book's 298 pages cover a broad chronology of the program and include both huge successes like the Mercury *Freedom 7* capsule and failures like the *Vanguard TV3* satellite. Muir-Harmony tells with great detail and historical context how each of the 50 objects played its part in putting humans on the Moon.

Not all of Muir-Harmony's choices are obvious. One example of an object many others might never consider an Apollo artifact is the chair John F. Kennedy used during his televised debate with Richard Nixon in 1960. But as you read the author's account of the story behind that world-changing discussion in front of 70 million Americans, you realize that it's not just the artifacts that are important to the story, but the people behind them.

Apollo to the Moon brings some of those people to the forefront through what the author calls "Apollo VIP" sections. Nestled between the discussions of the objects, those sections highlight the achievements of notable figures involved in every step of the Apollo program. Some of the VIPs are obvious candidates—for example, Margaret Hamilton, the brilliant software engineer who was one of the key programmers on the Apollo guidance computer. But it is the less well-known figures like George Carruthers, a US Naval Research Laboratory engineer who worked on the far-UV camera and spectrograph that still sits on the lunar surface, whose stories will make readers eager to learn more.

Muir-Harmony describes each object's point of manufacture, its materials, and its dimensions before diving into its historical background and her rationale for including it. The first artifact showcased in *Apollo to the Moon* is the pieces of the Wright flyer that the *Apollo 11* crew took to the lunar surface. By starting with the Wright brothers, Muir-Harmony steps away from a focus on Apollo as an engineering feat, something she continues to do throughout the book, and instead taps in to the broader history and humanity of the missions. Neil Armstrong's desire to honor the Wright brothers says as much about the man as it does about the objects. The Wright flyer probably carries as much significance for the first Moon landing as does the first Saturn V rocket.

Although the 1960s space programs Mercury, Gemini, and Apollo were largely politically motivated by the space race with the USSR, they nonetheless delivered outstanding science that we're still studying. The example in the book is that of the Apollo Moon rocks. The author talks about the number of rocks returned from each mission and the information we gained from them. That chapter gives the reader a taste of how important those rocks have been to our scientific understanding about how the Moon was formed.

Apollo to the Moon closes with a nod to the “new space”—the modern space race largely being driven by commercial entities. The inclusion of Amazon CEO and Blue Origin founder Jeff Bezos, who oversaw the remarkable recovery of the Apollo F-1 engines from the depths of the Atlantic Ocean and their subsequent restoration, is a fitting footnote.

My only criticism of this book is that it leaves you wanting more—more objects, more backstory, more VIP tales. Every page made me think of other objects and stories that deserved their own spotlights. I hope that the author expands on this book—perhaps taking inspiration from the British Museum’s ground-breaking “History of the World in 100 Objects” audio series broadcast by the BBC in 2010.

To say this is simply a book about objects would be doing it a great disservice. *Apollo to the Moon* reaches out to everyone—not just spaceflight historians or those interested in technical detail, but all those who want to know more about how, a half century ago, an impossible dream became reality. Although it has now been more than 50 years since humanity first reached our nearest celestial neighbor, we’re still marveling at its brilliance.

Nick Howes
Aerolite Meteorites
Wiltshire, UK

GAVRAN333/123RF

A 2014 Serbian stamp honoring Mileva Marić.

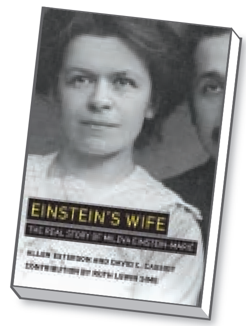
Getting to know Mileva Marić

After Albert Einstein became an international celebrity, his Serbian ex-wife Mileva Marić considered drafting her memoirs. Yet Einstein rudely dissuaded her, saying that no one would be interested in someone so “completely insignificant.” But Einstein was wrong: Countless people are now interested in Marić. In 1929 her Serbian friend Milana Stefanović talked to a newspaper reporter and insinuated that Marić had contributed to Einstein’s famous works. Marić herself chose not to be interviewed, but decades later, some Serbians argued that she was secretly a great physicist.

Einstein’s Wife: The Real Story of Mileva Einstein-Marić reconstructs Marić’s early life fairly and accurately. The compact volume will be an informative addition to library collections and a fascinating account for curious readers. Historian of science David Cassidy lucidly recounts her youth in school and her college years. Marić and Einstein were classmates at Zürich Polytechnic (now known as ETH), where they became romantically involved, leading to what Cassidy calls their “unsuccessful” marriage. Chemist and historian Ruth Lewin Sime contributes a brief essay about women in science in the 1900s.

Most notably, Allen Esterson, a retired lecturer at Southwark College in London, extensively debunks many common but unsupported stories about Marić’s mathematical abilities and her role in Einstein’s most famous papers. The now-popular claim that Marić was Einstein’s secret collaborator lacks solid footing. The book builds on previously published works to systematically confront the myth and the underlying evidence that allegedly supports it. Researchers such as Albrecht Fölsing, Abraham Pais, John Stachel, Gerald Holton, Jeremy Bernstein, and I have published scholarly articles about Marić and Einstein, but nothing in the existing literature is as

Einstein’s Wife
The Real Story of Mileva Einstein-Marić
Allen Esterson and David C. Cassidy, with Ruth Lewin Sime
MIT Press, 2019. $29.95



comprehensive as what Esterson has done here.

Esterson meticulously addresses the fictions about Mileva Marić that have been circulating in nonscholarly books, online, and on television. Many of her self-proclaimed supporters are engaged in a game of speculative charity, one that Marić herself never requested. For example, in 1969 a retired Serbian science teacher, Desanka Trbuhović-Gjurić, published a glowing biography of Marić that ascribed mathematical brilliance to her and blamed her relative obscurity on sexism. Yet Esterson carefully shows that the book is unfortunately riddled with hearsay, fictions, and mistakes. Another Serbian author, Dord Krstić, published a book about Marić in 2004; like Trbuhović-Gjurić’s account, Krstić’s has some merits but is biased and distorted by the desire to elevate his Serbian heroine.

To be sure, those Serbian writers were correct about the obstacles that Marić faced as a female student of science in the 1890s. In *Einstein’s Wife*, Cassidy rightly explains the difficult odds that Marić had to overcome as a female student in a nearly all-male high school in Zagreb given the oppressive, structural gender discrimination at the time. She surmounted obstacles with special permissions and personal drive.

Esterson and Cassidy provide the

best account anywhere of Marić's actual talents and shortcomings in mathematics and physics, based on primary sources about her education. Although the pair unearthed only a handful of new sources, the new sources include Marić's high school transcripts from Zagreb. Those transcripts show that in physics and math, her grades ranged from "satisfactory" to "very good." In those transcripts, her only grade of "excellent" was in Greek. Although high school grades are certainly no final measure of intelligence or potential, Esterson and Cassidy's work shows that the historical record offers little support for the claim that Marić was a mathematical luminary, nor did Marić make such a claim herself.

One popular story about Marić is that as a student at Zürich Polytechnic, she was better at mathematics than Einstein, and therefore he later needed her help to draft his theories. That myth was advocated by Trbuhović-Gjurić and more recently echoed in the National Geographic television miniseries *Genius*. On the contrary, Einstein's college math grades were higher in three of the mathematics courses they took together and equal to hers in all others. Plus, he excelled in courses she didn't take, such as Differential Equations. Marić's average scores in mathematics were 4.5/6 (that is, 75%), and just 3.75/6 (63%) in descriptive geometry. Those were not high averages; many other students had higher averages, including Einstein. She twice took the final exams necessary to graduate from the Polytechnic, but, unfortunately, both times she failed her examination on the theory of functions.

Still, did Marić help Einstein in physics?

Yes! But the key question is, How much? One thing missing in this valuable book is a concise summation of Marić's importance in Einstein's scientific trajectory. So here it is.

They studied together in college and did independent readings in physics. In letters from 1899 to 1901, he credited her as sharing his aspirations in physics, and in a letter dated 27 March 1901, he referred to "our work on relative motion" of the invisible ether. The existing evidence suggests that Marić helped Einstein in some of his earliest efforts to draft physics papers in 1901. She supported him in the years when, he said, he was rejected by all physicists in Europe, which led him to become a mere government bureaucrat. With her and a few friends, Einstein discussed his amateur research that led to his first published papers. Apparently, she was the first person to read Einstein's original manuscript on special relativity. Reportedly, she, too, was the first person to actually believe it.

That is all important, even if she wasn't his secret coauthor.

However, after their daughter and son were born, Marić seems not to have worked on physics research at all. For example, her letters to her friend and confidante Helene Savić show no evidence that Marić continued working on physics after 1901. Instead, she repeatedly commented that Einstein was "tirelessly" writing many physics papers; by 1909 she was writing that "he really does deserve" the recognition he was finally getting.

Alberto Martínez
University of Texas at Austin

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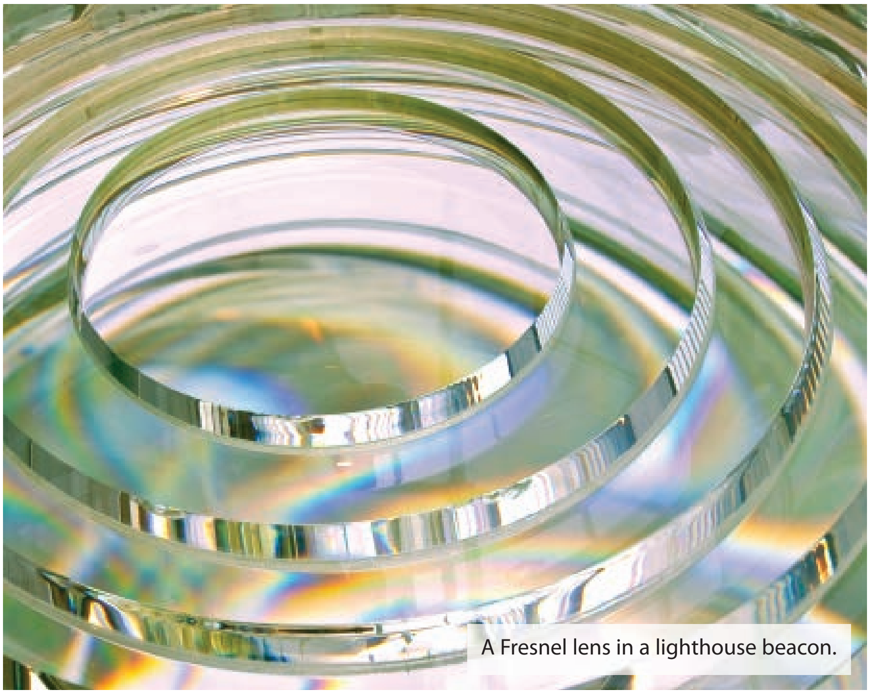
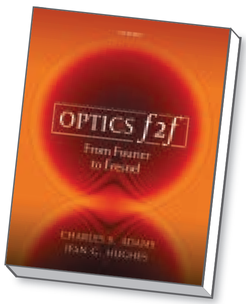


A Fresnel lens in a lighthouse beacon.

Exploring light propagation with Fourier and Fresnel



Optics f2f
From Fourier to Fresnel

Charles S. Adams and Ifan G. Hughes
Oxford U. Press, 2019. $39.95 (paper)

Standard texts for undergraduate optics courses include *Optics* by Eugene Hecht (5th edition, 2017) and *Introduction to Optics* by Frank Pedrotti, Leno M. Pedrotti, and Leno S. Pedrotti (3rd edition, 2007). Those texts use a traditional approach to teaching optics by starting with geometrical optics and moving to physical optics. Hecht's inclusion of historical details adds richness and humanity to the development of our understanding of light, although the stories frequently interrupt the book's conceptual flow. The Pedrottis skip the history lessons and add an engineering perspective that includes topics such as electro-optics, acousto-optics, and displays and detectors that are not traditionally covered in undergraduate optics courses. Those topics are useful in understanding current applications of optics but are not integrated into a coherent narrative.

In their new textbook, *Optics f2f: From Fourier to Fresnel*, Charles Adams and Ifan Hughes present a different approach to understanding optical phenomena that complements those two more traditional textbooks. Both authors hail from Durham University, where for many years they have been using Fresnel's and Fourier's ideas as a unifying theme in their undergraduate optics courses. The book is the culmination of their compiled notes. Adams, who specializes in quantum optics, received the Institute of Physics' 2014 Thomson Medal and Prize; Hughes, an expert on ultracold atoms, is the coauthor, with Thomas Hase, of *Measurements and Their Uncertainties: A Practical Guide to Modern Error Analysis* (2010).

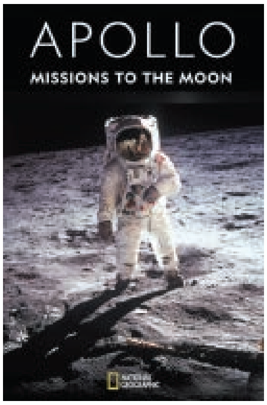
Adams and Hughes use the superposition of waves as a foundation for exploring light propagation. They start with Maxwell's equations with single plane and spherical waves and move to situations involving a few waves—topics that also appear in standard texts. But to explore wave optics, Adams and Hughes make the unique choice to use Fresnel's and Fourier's methods of adding many waves. Fresnel's approach considers the superposition of curved wavefronts, while Fourier focuses on the superposition of plane waves. The authors then provide a thorough discussion of Fourier optics, Fraunhofer diffraction, and Fresnel diffraction from a valuable perspective that differs from current optics texts. Adams and Hughes go on to examine contemporary topics, including laser beams and waveguides, tightly focused vector fields, unconventional polarization states, optical phenomena in the time domain, and light-matter interactions.

The book has 13 chapters. Each is made up of short sections of one to a few paragraphs that focus on fundamental ideas. Those sections make it easy for students to zero in on important concepts and equations and for instructors to select the exact material they want to cover. Unfortunately, the conciseness of the text will leave readers who prefer more expansive discussions wanting more. The authors put historical details and parenthetical comments either in separate sections or in boxes on the margins. That approach works well and preserves the flow of the main text. The book is appropriate for upper-level undergraduate optics courses. It would also serve as a handy reference text for graduate-level research students, perhaps as a companion to *Introduction to Modern Optics* by Grant Fowles (2nd edition, 1989).

Optics f2f includes 200 end-of-chapter exercises that help students prove steps that are left out of the in-text derivations, complete interesting new derivations, and develop conceptual understanding of the text topics. Occasionally the authors provide Python coding exercises to help students visualize the evolution of wave phenomena in space or time. The numerical problems are limited. The book provides limited resources for instructors at www.dur.ac.uk/physics/opticsf2f; at the time of writing, the page hosted a PowerPoint presentation containing images of the simulations from chapter 5 and selected solutions to the chapter exercises. Some examples of Python code used to generate figures in the text have been posted at the authors' personal webpage, piphase.wordpress.com.

Martha-Elizabeth Baylor
Carleton College
Northfield, Minnesota

NEW BOOKS & MEDIA



Apollo

Missions to the Moon

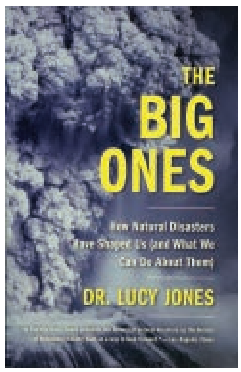
National Geographic Channel, 2019.

Director Tom Jennings (*Challenger Disaster: Lost Tapes*) combines restored archival audio and film footage in this new documentary about the history of the Apollo missions. Space history enthusiasts will appreciate that Jennings discards modern talking heads and background narration in favor of letting the historical film and audio tell the story; that choice allows the film to capture the feeling of watching these events unfold over the course of the 1960s. Overall, *Apollo: Missions to the Moon* is a solid and interesting documentary. However, it suffers in comparison to *Apollo 11*, released in theaters and IMAX earlier this year (see PHYSICS TODAY, May 2019, page 63), which also combines recovered archival film and audio but tells its story in a more engaging and technically detailed way. That said, Jennings does emphasize some themes missing from *Apollo 11*, including the experiences of NASA civilian employees and the astronauts' families along with public criticism of the space program. The film will air on the National Geographic Channel at 9pm EDT on 7 July. —MB

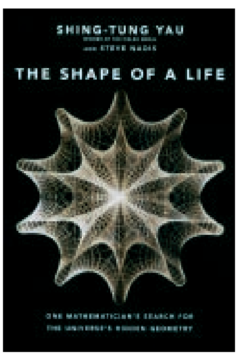
The Big Ones

How Natural Disasters Have Shaped Us (and What We Can Do About Them)

Lucy Jones
Anchor Books, 2019. $16.95 (paper)



From Mount Vesuvius erupting over Pompeii in AD 79 to the 2011 Tohoku earthquake in Japan, natural disasters are an inevitable part of life on Earth. Earthquakes and other geologic phenomena occur daily, yet they can prove catastrophic in heavily populated areas. Seismologist Lucy Jones, a 33-year veteran of the US Geological Survey, discusses some of the world's greatest catastrophes and how people have dealt with them. By looking at the past, Jones says, we can better plan for the future. —CC



The Shape of a Life

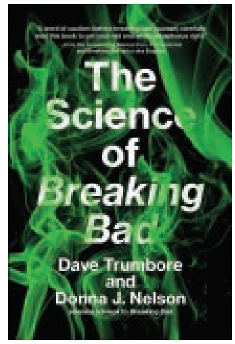
One Mathematician's Search for the Universe's Hidden Geometry

Shing-Tung Yau and Steve Nadis
Yale U. Press, 2019. $28.00

Mathematician Shing-Tung Yau won the Fields Medal in 1982 for, among other achievements, his proof of the Calabi conjecture, which has formed the basis for much of modern string theory. In this readable new autobiography, cowritten with science writer Steve Nadis, Yau tells the story of his personal and intellectual journey. The book covers his childhood in China and Hong Kong; his education at the Chinese University of Hong Kong and the University of California, Berkeley; and his eventual path to Harvard University and the work that won him mathematics' most prestigious prize. Yau and Nadis dive into explanations of some extremely complicated math and do so with an enviable clarity and precision. The book also offers a compelling portrait of the intellectual life of a mathematician. *The Shape of a Life* frequently talks about the conferences and colleagues that inspired Yau and influenced his work, a welcome antidote to the stereotype of the solitary theorist locked away in his office. —MB

The Science of Breaking Bad

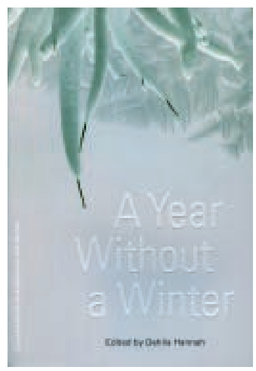
Dave Trumbore and Donna J. Nelson
MIT Press, 2019. $19.95 (paper)



Based on the popular TV series, *The Science of Breaking Bad* focuses on the many ways in which real-world chemistry is presented in the show. The premise of the series is that a mild-mannered high school chemistry teacher diagnosed with a terminal illness is driven to manufacturing methamphetamine to secure his family's financial future before he dies. Although the program is not a how-to guide for illicit drug making, it does present numerous instances of ad hoc chemistry, such as explosions, poisonings, and gassing of rival drug dealers. Coauthor Donna Nelson, a chemistry professor who served as science adviser for the series, not only fact-checked the science for the book but also shares insider information and anecdotes about her personal experiences from the show. —CC

A Year Without a Winter

Dehlia Hannah, ed.
Columbia Books on Architecture and the City, 2019. $23.00 (paper)

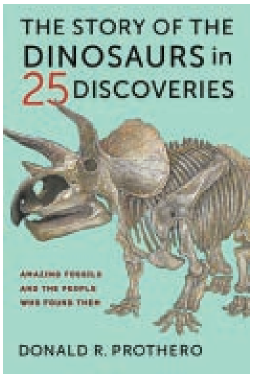


This collection of scholarly essays, visual art, and science fiction explores humanity's place in the environment in the context of climate change. Editor Dehlia Hannah brings together a fascinating collection of contributors, including literary scholar Gillen D'Arcy Wood, geochemist Hilairy Hartnett, and Hugo Award–winning author Nnedi Okorafor. The text also includes excerpts from older fiction and poetry about nature and climate, including several passages from Mary Shelley's *Frankenstein*. —MB

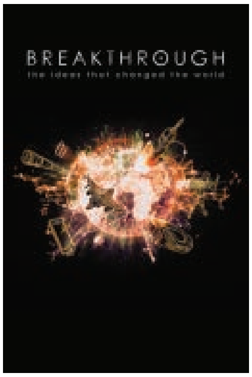
The Story of the Dinosaurs in 25 Discoveries

Amazing Fossils and the People Who Found Them

Donald R. Prothero
Columbia U. Press, 2019. $35.00



Donald Prothero, author of *The Story of the Earth in 25 Rocks: Tales of Important Geological Puzzles and the People Who Solved Them* (2018), returns with another entertaining trip through the history of science, this time focusing on paleontology. *The Story of the Dinosaurs in 25 Discoveries* recounts major fossil finds, including well-known species like *Triceratops* and more obscure ones like *Patagotitan.* He also tells the stories of the people who made those discoveries; his account of the feud between Edward Drinker Cope and Othniel Charles Marsh is especially entertaining. Readers interested in the latest paleontological literature will appreciate the list of references at the end of every chapter and Prothero's readable discussions of important papers and arguments in the field. —MB



Breakthrough

The Ideas That Changed the World

PBS, 2019. $34.99 (DVD)

This six-episode PBS miniseries takes a fine-grained, fascinating look at the history of important technologies. Each episode focuses on an invention or object, such as the telescope, the car, or the rocket, and looks at both the object's historical significance and the scientific advances that went into its development. Actor Patrick Stewart narrates, but unfortunately the lines he's given are often pretentious and clunky: The first episode opens with the words "since the dawn of humankind," a painful cliché that never should have made it past a first draft. The background music is also heavy-handed and distracting. But the interviews with researchers and the broad-ranging perspectives on the history of the objects are informative and interesting. The series will be released on DVD and via digital download on 9 July. —MB PT

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

Andreas Mandelis

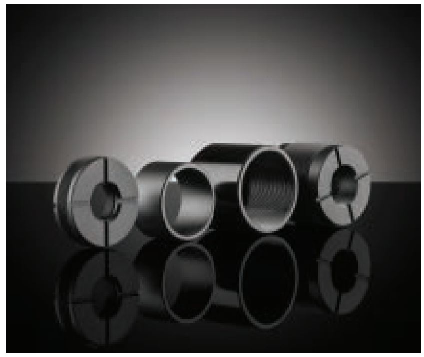
Q-TOF mass spectrometer

Agilent has launched its 6546 quadrupole time-of-flight (Q-TOF) liquid chromatography–mass spectrometry (LC/MS) system, which lets analysts acquire high-resolution data across a very wide dynamic range. According to Agilent, the instrument's data-independent Q-RAI (quadrupole-resolved all ions) acquisition mode reduces the complexity of tandem MS spectra while maximizing the accuracy and quality of the data acquired. The MassHunter Quantitative Analysis 10.0 software includes features that allow laboratories to quickly and accurately screen complex sample sets for target and suspect compounds in a single workflow. Applications for the new LC/Q-TOF include metabolomics research, environmental screening, and food testing. ***Agilent Technologies Inc****, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

Noninvasive plasma chamber health monitoring

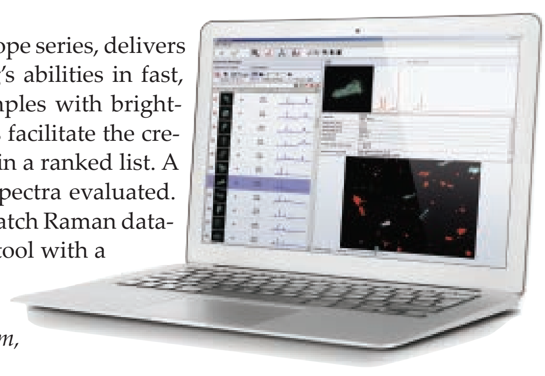
According to Impedans, its Moduli RF spectrometer is the first instrument to allow users to directly monitor the electrical state of a plasma from outside the plasma chamber without modifying their plasma tool. The radio emission spectroscopy tool can be placed outside the plasma source—for example, at a window port or near a turbo pump. It can detect air leaks, wafer displacement, and other serious plasma faults in real time. The antenna is split into two parts, so the antenna pickup can go within the RF shielding and the amplifiers outside. The radio antenna collects the electric and magnetic waveforms from the chamber and sends them to the acquisition unit, which extracts the RF harmonics. The harmonic spectrum is very sensitive to small changes in plasma impedance, a key indicator of process repeatability. ***Impedans Ltd****, Chase House, City Junction Business Park, Northern Cross, Dublin 17, D17 AK63, Ireland, https://impedans.com*

Multielement tube system



The versatile mix-and-match components in Edmund Optics' Techspec multielement tube system let users prototype and create uncommon optical designs. The system combines multielement outer tubes with multielement inner single and pair optic mounts. The outer tubes have M29 threads running down their entire length; inner mounts have M29 threads along their outer diameters, so they can be placed anywhere within an outer tube. The design allows for infinitely adjustable optical spacing along the optical axis. To ease adjustment, a custom-designed multielement tube spanner wrench has a hollow bore to let a beam pass through. The system can be further customized using spacer rings and tubes, inner apertures, and additional accessories. It accommodates circular optics with diameters from 5 mm to 25.4 mm and edge thicknesses up to 17 mm. System lengths, which can range from 15 mm to 100 mm, can be combined to expand capabilities. ***Edmund Optics Inc****, 101 E Gloucester Pike, Barrington, NJ 08007, www.edmundoptics.com*

Particle analysis for Raman imaging



ParticleScout, a particle analysis tool for WITec's alpha300 Raman microscope series, delivers an accelerated workflow while making use of confocal Raman imaging's abilities in fast, label-free, and nondestructive chemical characterization. It surveys samples with bright- and dark-field illumination to view the particles in them. Optical images facilitate the creation of a mask used to categorize particles of interest and arrange them in a ranked list. A Raman spectrum is automatically acquired from each particle and the spectra evaluated. The particles can be identified manually or by using the integrated TrueMatch Raman database software. According to WITec, the integration of a particle analysis tool with a Raman database is unique in the industry. ParticleScout is suitable for use in such fields as environmental science, geology, and microplastics and pharmaceuticals research. ***WITec GmbH****, Lise-Meitner-Str 6, D-89081 Ulm, Germany, www.witec.de*

Laser scanning microscope upgrade kit

A laser scanning microscope upgrade kit from PicoQuant expands the ability of Scientifica's HyperScope and VivoScope multiphoton microscopes to support fluorescence lifetime imaging (FLIM). Kit users can simultaneously acquire fluorescence intensity and lifetime images in up to two color channels. The combination of imaging techniques allows, for example, the acquisition of highly quantitative information regarding molecular interactions, the quantification of biosensor measurements, and the determination of absolute ion concentrations. Users gain access to time domain information, which can potentially enable such applications as the easy quantification of Förster resonance energy transfer experiments and the study of environmental parameters. The Scientifica FLIM upgrade kit supports galvo and resonance imaging and PicoQuant's rapidFLIM approach, with peak photon rates up to 1.5 Gcounts/s. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Double-pulse lasers for LIBS

A series of neodymium-doped yttrium aluminum garnet lasers from Litron Lasers are fitted with low-divergence optics to ensure a high degree of focusing and make them suitable for laser-induced breakdown spectroscopy (LIBS) applications that use the double-pulse technique. The Bernoulli LIBS series has two laser oscillators combined onto a single beam axis in a single vibration- and shock-proof, fully sealed laser head. Two motorized attenuators allow for independent energy adjustment of each laser. The compact lasers have output energies up to 250 mJ at 1064 nm and repetition rates up to 30 Hz. They feature fast-detachable connections, ruggedized oscillators, motorized safety shutters, intelligent microprocessor control and monitoring of all laser parameters, and a LUCi remote interface for ease of use. ***Litron Lasers Ltd***, *8 Consul Rd, Rugby, Warwickshire CV21 1PB, UK, www.litronlasers.com*

Ultracompact spectrometer

The Pebble VIS OEM spectrometer from Ibsen Photonics combines an ultracompact form factor with high resolution, high sensitivity, and environmental ruggedness. At Pebble's core is an efficient transmission grating manufactured by Ibsen: It makes possible a resolution of 6 nm across the full 380- to 850-nm-wavelength range. According to the company, that is among the highest for this size spectrometer. Pebble uses a fast, sensitive CMOS detector array with 256 pixels. When combined with a large numerical aperture of 0.22 (low f-number of f/2.2), Pebble provides very high sensitivity for a small spectrometer. Pure transmission-based optics ensure a very good thermal stability. Pebble is suitable for use in handheld and portable spectroscopy instruments for applications such as fluorescence and color measurements. ***Ibsen Photonics A/S***, *Ryttermarken 17, DK-3520 Farum, Denmark, https://ibsen.com*

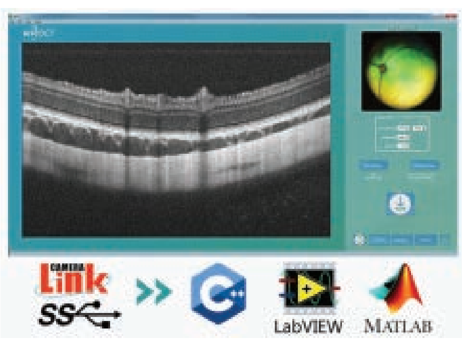
Compact high-performance spectrometers

To bridge the gap between costly research laboratory systems and small economical ones, StellarNet has designed instruments that deliver high-performance spectroscopy measurements in a compact form. The Hyper-Nova spectrometers use a back-illuminated, deep-depletion detector technology that, according to the company, provides the lowest background noise possible in a compact spectrometer. The Hyper-Nova's CCD detector is vacuum-sealed and cooled to −80 °C, with peak quantum efficiencies up to 95%. Various wavelength configurations include specialty ones for Raman spectroscopy at 785 nm and 532 nm, 300–1100 nm optical spectroscopy, and custom low-light applications. High-scattering samples can be measured with the smallest of the available interchangeable slits for highest resolution; weak Raman can be measured with a larger slit to allow for increased light throughput. ***StellarNet Inc****, 14390 Carlson Circle, Tampa, FL 33626, www.stellarnet.us*

Microscopes for spectroscopy

With the accessories included in the Standard Microscope Spectroscopy systems now offered by Horiba Scientific, a standard microscope can be fitted with a spectrometer and a detector. The microscope can then be used to perform techniques such as Raman, steady-state and time-resolved photoluminescence, reflectance/transmittance, electroluminescence, and photocurrent and dark-field scattering. The flexible, modular platforms let users leverage an existing standard microscope or create a turnkey system that performs the microscopy function and adds one or more spectroscopies as a complementary technique. The company's Optical Spectroscopy Division can design systems that meet users' individual research or application needs. ***Horiba Scientific Division of Horiba Instruments Inc****, 20 Knightsbridge Rd, Piscataway, NJ 08854, www.horiba.com/scientific*

Software for OCT system development



Wasatch Photonics has announced its WP OCT software platform. Optical coherence tomography (OCT) is a fast-growing imaging technology with applications as a primary and complementary diagnostic tool in medicine and industry. The suite of software development kits, sample graphical user interfaces, and turnkey application software facilitates imaging speeds of up to 250 kHz with minimal software development effort. It has the flexibility to customize user interface, algorithms, and analysis. Availability in C++, C#, Matlab, and Labview environments makes the platform versatile, as does compatibility with Camera Link and USB 3.0 data acquisition protocols. The software provides high-level computational capability for efficient data analysis using powerful yet flexible graphics processing unit platforms compatible with the fastest OCT spectrometers currently available. ***Wasatch Photonics****, 4022 Stirrup Creek Dr, Ste 311, Durham, NC 27703, https://wasatchphotonics.com*

Spectrograph and scanning monochromator

Teledyne Princeton Instruments has added a spectrograph and scanning monochromator with a 750 mm focal length to its SpectraPro HRS series. The HRS-750 features astigmatism-corrected optics and a mechanical scanning range of 0–1500 nm. Its resolution is 0.05 nm or better. According to the company, its ResXtreme spectral deconvolution technology enhances spectral resolution, peak intensities, and consistency across the 2D focal plane by as much as 60%. Its AccuDrive technology improves wavelength accuracy and repeatability over previous scan systems and increases grating-to-grating wavelength precision to subpixel repeatability. Among the applications for the SpectraPro HRS-750 are Raman spectroscopy, photoluminescence, fluorescence, laser-induced breakdown spectroscopy, plasma diagnostics, transmission, absorption, and microspectroscopy. ***Princeton Instruments****, 3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com*

Near-IR microspectrometer

AP Technologies has unveiled the latest MEMS grating-collimator microspectrometer from OtO Photonics. It claims the RedSparrow-Series RS1680 brings the size, performance, and cost benefits of the company's UltraMicro-Series technology to the near-IR band. The instrument uses a 128-pixel near-IR indium gallium arsenide sensor for operation from 950 nm to 1700 nm with a full width at half maximum resolution of 8–13 nm. OtO's MEMS-based microspectrometers replace the collimator-plane grating-focusing mirror optical structure used in traditional Czerny–Turner spectrometers with a nonspherical, mass-producible microsized component that combines grating and focusing functions. The microchip concave grating technology leverages patented algorithms to calculate curvature and ray tracing to eliminate aberrations. ***AP Technologies Ltd****, The Coach House, Watery Ln, Bath BA2 1RL, UK, www.aptechnologies.co.uk*

Extended-range spectrometer

A new version of the HDX high-definition spectrometer from Ocean Optics covers the UV to the near-IR range. The Ocean HDX-XR has an extended-range (XR) 200–1100 nm grating and a 10 μm slit. According to the company, it delivers high spectral performance, with ±0.5 pixel thermal stability, high throughput, and low stray light. The spectrometer features a back-thinned CCD, a dynamic range of 12 000:1, a signal-to-noise ratio of 400:1, and optical resolution of 1.0 nm full width at half maximum. It has an onboard memory of 50 000 spectra. Applications for the HDX-XR spectrometer include health and life sciences, LED measurements, plasma monitoring, and photovoltaic and polymer analysis. ***Ocean Optics Inc****, 8060 Bryan Dairy Rd, Largo, FL 33777, https://oceanoptics.com*

Dual-beam UV-visible spectrophotometer

The DS5 UV-Vis Spectrophotometer from Edinburgh Instruments is a user-friendly, dual-beam instrument that measures absorption and transmission as a function of wavelength. It can be used for a wide range of sample types and measurements and is suitable for many analytical applications in which accurate and precise measurements are key to results. Additional benefits include stray light attenuation, baseline flatness, wavelength and photometric accuracy, and reproducibility. The instrument features a dual lamp, a Czerny–Turner configuration monochromator, and a compact footprint. It offers user-selectable variable bandpass options at 0.5, 1.0, 1.5, 2.0, and 4.0 nm. Fast scanning up to 6000 nm/min aids sample analysis throughput. ***Edinburgh Instruments Ltd****, 2 Bain Sq, Kirkton Campus, Livingston EH54 7DQ, UK, www.edinst.com*

OPO laser system

Toptica offers its DLC TOPO high-power CW optical parametric oscillator (OPO) laser system for challenging applications in molecular spectroscopy, quantum optics, materials testing, biophotonics, and physical chemistry. The system integrates a distributed feedback seed laser, a fiber amplifier, OPO, and the company's DLC pro digital laser control. A large mode-hop-free tuning range up to 300 GHz enables visibility of full spectroscopic signatures, and a 2 MHz linewidth reveals narrow atomic and molecular features. For ease of use, no modules need to be exchanged or manual adjustments made. Convenient digital control over the full 1.45–4.00 μm spectral range enables coarse wavelength tuning, fine-tuning, and frequency locking. The DLC TOPO is only available in North America. ***Toptica Photonics Inc****, 5847 County Rd 41, Farmington, NY 14425, www.toptica.com* PT

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Charles Kuen Kao

Charles Kuen "Charlie" Kao was a man who transcended the usual categories that we use to pigeonhole scientists and engineers. At home throughout the world and a citizen of both the US and the UK, he remained deeply rooted in Hong Kong, where he returned for extended periods throughout his life. A Catholic by choice, he remained attached to Chinese culture; his grandfather was a famous scholar and poet, and Charlie was a lover of Chinese novels and crafts. While maintaining friendships throughout the world, he was a devoted family man; he kept close ties with a widespread family and was married for 59 years to May-Wan "Gwen" Wong, who was his intellectual and personal partner.

Considered introverted in his youth, Charlie became a charismatic scientific leader who repeatedly assembled teams of scientists and engineers to tackle problems of importance to society. He thought of himself as an engineer and focused on problems whose solutions would better the human condition, but in the process he made important contributions to fundamental science. He worked in academia, in industry, and with government.

Charlie was born on 4 November 1933 in Shanghai, China. His family moved to British Hong Kong in 1948, and he got his secondary education at St Joseph's College. After graduating, he went to the UK, where he attended Woolwich Polytechnic (now the University of Greenwich) and obtained a bachelor of engineering degree in 1957. While working at Standard Telecommunication Laboratories (STL), he became interested in optical waveguides. He registered as an external student at University College London in 1963, and in 1965 he obtained his PhD under the supervision of Harold Barlow. Charlie's dissertation was on millimeter and submillimeter electromagnetic waves in waveguides.

At STL, Charlie became part of a team that was exploring alternatives to existing telecommunications that used coaxial cables or radio signals and operated at megahertz frequencies. The researchers looked at hollow metal waveguides that could operate at gigahertz frequencies but ultimately rejected them. They then considered several optical waveguide designs in which the light would be mostly guided in air and thus avoid material losses. By 1965 Charlie was leading the STL team. He changed its focus to optical fibers, and in 1966 he and George Hockham, with Gwen's assistance, wrote a seminal paper in which they concluded that eliminating glass impurities would reduce losses below 20 dB/km, the threshold for commercial viability. Charlie realized that a worldwide effort was needed to turn that theoretical possibility into a reality, so he crisscrossed the globe and mobilized numerous participants in that ultimately successful effort.

Later in his career, Charlie became an advocate for engineering research and education. Good engineering requires a profound understanding of basic physical science combined with an ability to assess the effects of the engineering outcomes on society. Charlie founded the department of electronics (later the department of electronic engineering), which exemplified those values, at the Chinese University of Hong Kong (CUHK). Between 1974 and 1986, he worked at ITT Corp in the US, first as chief scientist and ultimately as director of corporate research.

In 1986 Charlie returned to CUHK as vice chancellor. During his tenure, he propelled CUHK into the front ranks of world-class research universities and in the process raised the level of all research universities in Hong Kong. He assembled talented researchers and started several new engineering departments. Charlie recognized early the growing importance of biotechnology and the internet, and he started research programs in those areas. He was an early advocate of environmentally conscious engineering and in 1972 wrote a paper on the subject. The strong partnerships he brokered among academic, industrial, and government stakeholders became a model for research universities in Hong Kong and ultimately for Mainland China and other countries in Southeast Asia.

Charlie was an advocate for free speech. Famously, when a student protest disrupted an important meeting and he was asked how the students should be punished, he responded, "Punishment? Why do I need to punish them? They have the freedom to express their views."

Charles Kuen Kao

CHARLES K. KAO FOUNDATION FOR ALZHEIMER'S DISEASE

Beginning in 2004 Charlie developed Alzheimer's disease. However, with help from Gwen (shown in the photo), he remained active. In 2009 he was a corecipient of the Nobel Prize in Physics for his work on fiber optics. He could no longer speak, but he appeared in Stockholm, with Gwen giving his acceptance speech. In 2010 he and Gwen set up a foundation to support people with Alzheimer's and their caregivers. Charlie's memoir, *A Time and a Tide*, was published in 2011. Charlie finally succumbed to the disease on 23 September 2018 while in hospice care in Hong Kong.

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Colin McCormick is the chief technologist of Valence Strategic LLC and an adjunct professor at Georgetown University's Walsh School of Foreign Service.

Self-driving cars find their way in the world

Colin McCormick

Sensors, sophisticated algorithms, and powerful onboard computing are the essential ingredients.

Self-driving cars, otherwise known as autonomous vehicles (AVs), are best thought of as rolling robots. By continuously sensing their surroundings, choosing a set of actions, and then implementing them, AVs can navigate various environments. That cycle of "sense, decide, and act" depends on a suite of sensors that feed data to various algorithms and an onboard computing platform to run the system in real time. To understand the trade-offs being explored by AV developers, it helps to start with the sensors.

Lights, camera, action

An AV is easy to spot on the road because of the unusual sensor package that juts up from its roof. A key part of that package is the light detection and ranging (lidar) unit. Automotive lidar, such as the system on the Ford Argo shown on the next page, is composed of an array of semiconductor lasers and optical detectors mounted on a rotating platform in an enclosure. By emitting pulses of near-IR light and measuring the return time of reflections, the system calculates a "point cloud" of objects surrounding the vehicle. The point cloud is updated at roughly 10 Hz, at a range of about 50–100 m, and with a spatial resolution of ±2 cm. But that density of high-resolution data comes at a price: Lidar units can cost tens of thousands of dollars.

AVs augment their lidar data with radar measurements. Operating at either 24 GHz or 77 GHz for short- or long-distance detection, respectively, radar has much lower spatial resolution than lidar. However, because it is easy to measure the Doppler shift of returned radar pulses, automotive radar can also determine the radial velocity of objects; that measurement, in turn, improves the AV's ability to track pedestrians and other vehicles. Radar works in rain, snow, and other weather conditions that can blind lidar. Another advantage: Radar units can be had for a few hundred dollars.

AVs use lidar and radar data for two main tasks. First, they determine their own position and orientation in space, a process known as localization. Coarse localization is possible with GPS—often augmented with gyroscopes and accelerometers—but autonomous driving requires much higher precision. AVs use algorithms to combine lidar and radar data in order to identify landmarks such as walls, trees, and signposts. The need for high-resolution "base maps" that locate those landmarks means that AVs are usually limited to operating in previously mapped areas. Generating, updating, and distributing those maps to AVs is an important operational challenge and one of the fastest-growing segments of the AV industry.

The second main task for lidar and radar aboard AVs is the identification and tracking of moving objects, including other vehicles and pedestrians nearby. Statistical algorithms such as Kalman filters maintain estimates of the current position and velocity of all tracked objects and update them using lidar and radar data. Sensors that can detect objects at long distances are particularly valuable for high-speed driving because every 50 m of additional range provides one additional second of warning about oncoming vehicles.

Besides lidar and radar, AVs use the digital video camera as a primary sensing technology. Multiple cameras are on the job—all using standard CMOS technology but with some focused on nearby objects and others focused farther away. Deep convolutional neural networks—a sophisticated form of artificial intelligence—analyze the images to detect and classify objects such as pedestrians, bicycles, stoplights, and other vehicles; to identify lane lines and open space on the road; to read street signs; and to perform other tasks. The information can be used to validate or veto proposed trajectories calculated by the AV based on lidar and radar data.

Path planning

AVs use information about their own position and velocity, the status of objects around them, and lane markings to make decisions about exactly where they should drive. The process, known as path planning, includes a higher-level, strategic component—for instance, whether the AV should switch lanes to pass a vehicle in front of it—and a lower-level, tactical component that determines the optimal steering angles and acceleration or braking to accomplish a maneuver with minimal jerk.

Path-planning algorithms attempt to meet several prioritized goals, from avoiding collisions to completing trips in the least time, as constrained by speed limits. They may also include higher-level decisions, such as determining the best overall street-by-street route to get from the start of a journey to its end.

An important aspect of the AV operational model is the different update rates of various sensory inputs and data processing. The sensors (lidar, radar, and cameras) update at high frequency (typically tens of hertz) to provide the AV with the most recent measurements of nearby objects and road conditions. The localization algorithm updates its estimate of the vehicle's

A FORD ARGO VEHICLE in action. Visible on the roof are two lidar units (top) and multiple video cameras (bottom).

position and velocity at medium frequency (typically a few hertz), and the path-planning algorithm updates its proposed near-term trajectory at the lowest frequency (typically around one hertz) to reflect the fact that physical maneuvers should be relatively smooth and consistent for safe driving.

Because most of those functions must be conducted in real time, all the data processing must be done aboard the vehicle. To maximize the processing speed, especially for the deep neural networks analyzing video-camera images, AVs typically use a graphics processing unit (GPU). The fact that the processors consume hundreds of watts has led AV designers to explore trade-offs between complex algorithms and power draw to avoid compromising the vehicle's overall fuel efficiency. GPUs are also used extensively in the offline training of neural networks; the data collected from many operating vehicles are fed into the networks and used to periodically update AV software.

The future of lidar

The use of lidar for AVs dates back to a 2005 Defense Advanced Research Projects Agency grand challenge: the first successful demonstration of autonomous driving in an uncontrolled environment. The top-finishing vehicles all used lidar devices for high-resolution spatial information about their surroundings. Since that time, almost all AV developers have built their systems around lidar devices, despite the high cost. A notable exception is Tesla, whose Autopilot semiautonomous system relies only on radar and video cameras but continues to face questions about its safety performance. By contrast, companies like Ford and Cruise Automation are experimenting with AVs using multiple lidar units that provide redundancy and enhanced spatial data.

As the single most expensive AV component, lidar has been the focus of intense R&D by industry. One area of interest is replacing the potentially failure-prone rotation architecture. Several companies are working to develop lidar based on microelectromechanical mirrors, optical phased-array techniques, and wide-field flash illumination. Those methods steer laser beams without bulk mechanical motion and may enable "smart" beam steering that would increase the density of lidar beams near identified objects to acquire more spatial information about them.

A second area of interest is eye safety. Wavelengths near 900 nm, which are typical in automotive lidar, can cause retinal damage. To minimize the hazard, the optical power is kept low. But that limits the sensitivity and range of the time-of-flight method. Some lidar developers have therefore begun using lasers at 1550 nm, which are less dangerous for eyes. The wavelength allows for higher power but requires more expensive indium gallium arsenide detectors.

Industry has also explored alternatives to time-of-flight detection. One of them is the frequency-modulated continuous-wave method, in which the lidar frequency is continuously changed. Using heterodyne detection, the lidar device measures the distance to a reflecting object by sensing the beat frequency between emitted and returned light. The technique is sensitive to the Doppler shift, so it potentially allows lidar to also detect radial velocity.

Another technique being developed is amplitude modulation, which works much like an optical lock-in detector. Amplitude-modulation devices could use lower optical power and might also provide a solution to lidar cross talk, a potential problem if multiple AVs operate in the same area.

Autonomous vehicles combine a wide array of cutting-edge technologies to create a system that can navigate under diverse conditions. AVs already demonstrate impressive technical performance in laboratories and on public roads, and the pace of innovation is rapid. You may find yourself riding in an autonomous vehicle sooner than you think.

Additional resources

▶ W. Schwarting, J. Alonso-Mora, D. Rus, "Planning and decision-making for autonomous vehicles," *Annu. Rev. Control Robot. Autonomous Sys.* **1**, 187 (2018).

▶ F. Rosique et al., "A systematic review of perception system and simulators for autonomous vehicles research," *Sensors* **19**, 648 (2019).

▶ J. Wallace, "Photonics products: Lidar systems: Automotive lidar draws heavily on photonics industry," *Laser Focus World*, 1 November 2018. PT

BACK SCATTER

Soap halos

Optics and soap bubbles were two passions of Belgian physicist Joseph Plateau (1801–83). He notably studied how the human eye captures images, and he formulated several rules, now known as Plateau's laws, that describe the structure of soap bubbles and foams. Those two interests unite in the optics of soap bubbles to generate intriguing patterns of light, including the ones shown in this photo. The patterns are the projections on a screen of three laser beams—two green and one red—scattered off a Plateau border, the tubular structure where three soap bubbles meet.

The Plateau border has a triangular cross section about 0.5 mm across and acts like a hyperbolic prism. The beams, each one with a different incident angle, get scattered into cones that are centered on the Plateau border axis and manifest as circular halos and arcs reminiscent of ice halos in the atmosphere (see Physics Today, February 2015, page 68). Additionally, the visible fringes are the telltale sign of wave optics, including diffraction by the Plateau border's three sharp edges. Alberto Tufaile and Adriana Tufaile at the University of São Paulo have investigated the breadth and details of such phenomena in terms of the geometrical theory of diffraction, which also describes the scattering of high-frequency electromagnetic waves in antennas. (A. Tufaile, A. P. B. Tufaile, *Phys. Lett. A* **379**, 529, 2015; **379**, 3059, 2015. Submitted by Adriana Pedrosa Biscaia Tufaile.)

—RJF

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