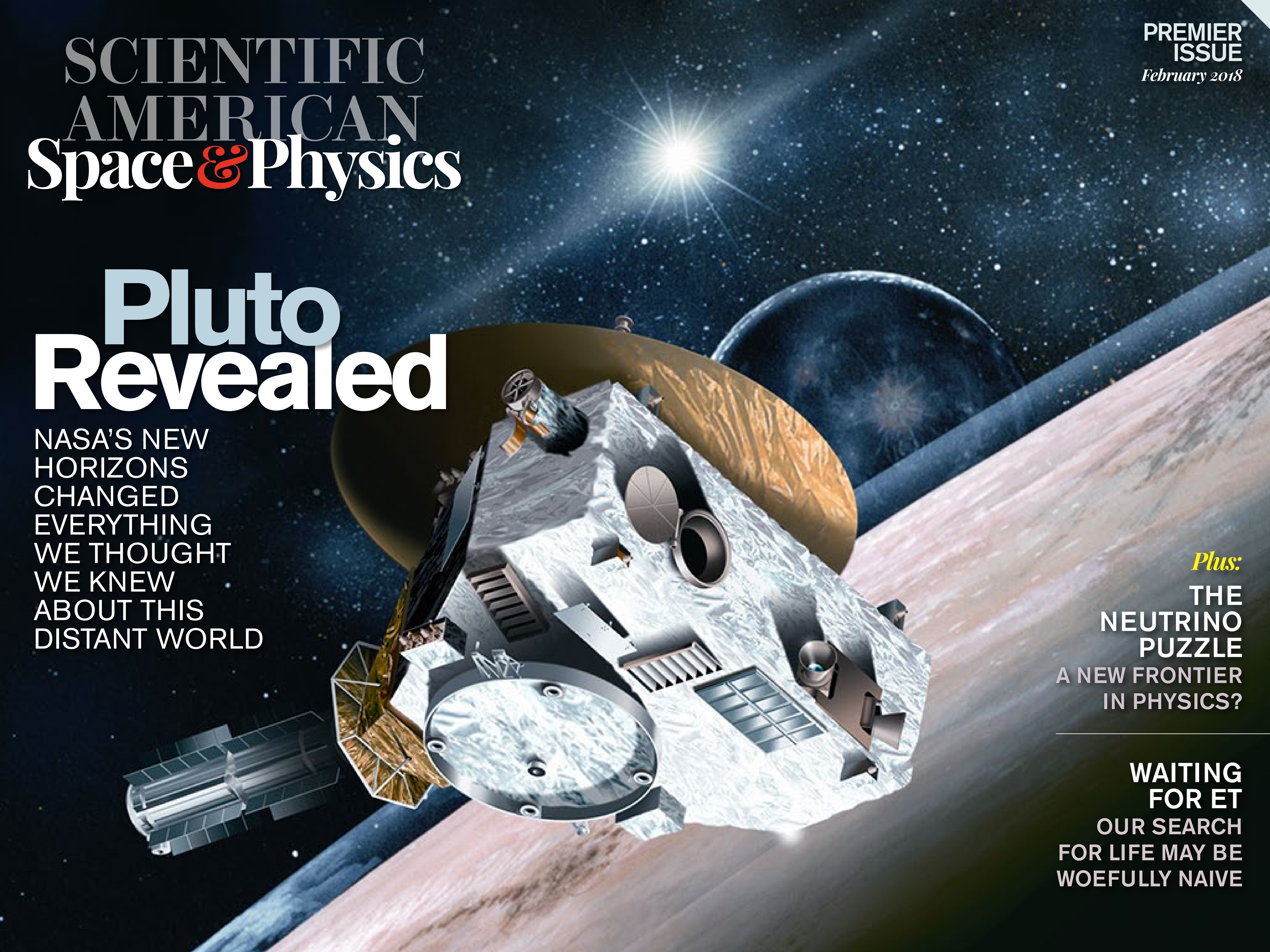

SCIENTIFIC AMERICAN
Space & Physics

PREMIER
ISSUE
February 2018

Pluto Revealed

NASA'S NEW HORIZONS CHANGED EVERYTHING WE THOUGHT WE KNEW ABOUT THIS DISTANT WORLD

Plus:

THE NEUTRINO PUZZLE

A NEW FRONTIER IN PHYSICS?

WAITING FOR ET

OUR SEARCH FOR LIFE MAY BE WOEFULLY NAIVE

FROM THE EDITOR

Far Out

Freshman year in Astronomy 101 at university: I'll never forget it. As I settled into the desk, notepad ready, the professor lowered the lights. We watched a video made up of grainy black-and-white images of Jupiter's Great Red Spot and the cloud bands above and below it. I was shocked. Until that moment, I'd only ever seen still pictures from space. The gases that composed the Red Spot spun rapidly—later, I learned, at hundreds of miles per hour. The cloud bands moved in different directions at different rates. I realized space was "alive"—ever changing, full of puzzles, beautiful, dangerous. I began to take further armchair journeys of discovery, to see more of these alien vistas, to learn more about the particles that made them up, and to try to understand the mechanisms that shaped them. It's been a lifelong passion at this point for me. And now, in this first edition of Space & Physics, we welcome you along for the ride. We hope you like it and look forward to your feedback.

Mariette DiChristina
Editor-in-Chief and Senior Vice President

SPACE & PHYSICS

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TAKE THE SURVEY

On The Cover

Artist's rendition of the New Horizons spacecraft flying over Pluto

ON THE COVER: JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE

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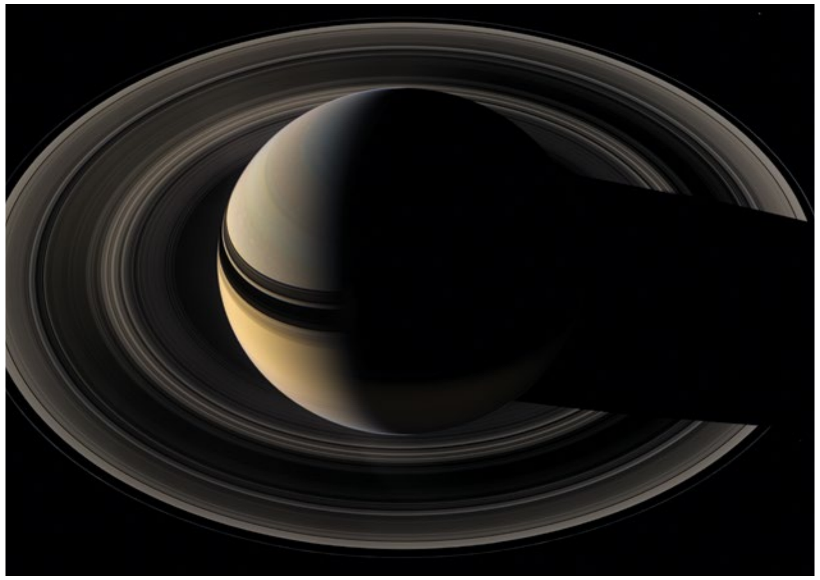
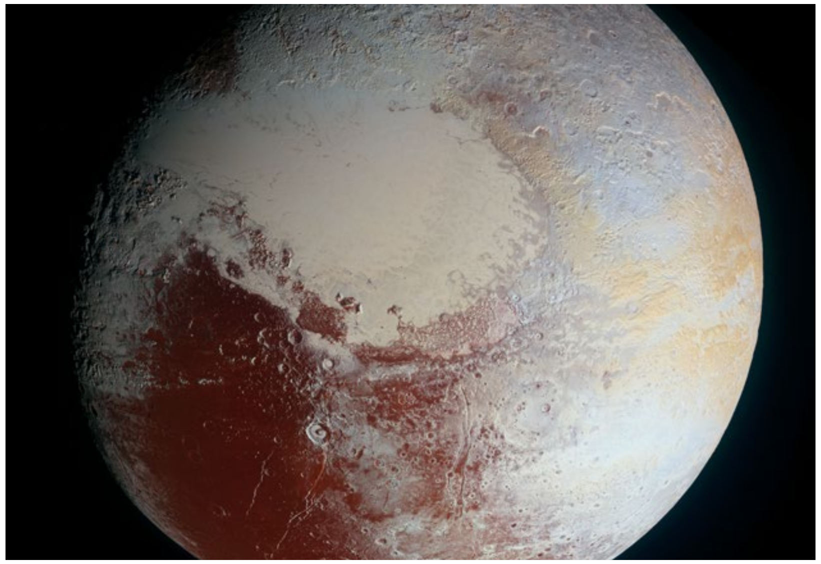


COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE

MARK ROSS STUDIOS



COURTESY OF NASA

OPINION

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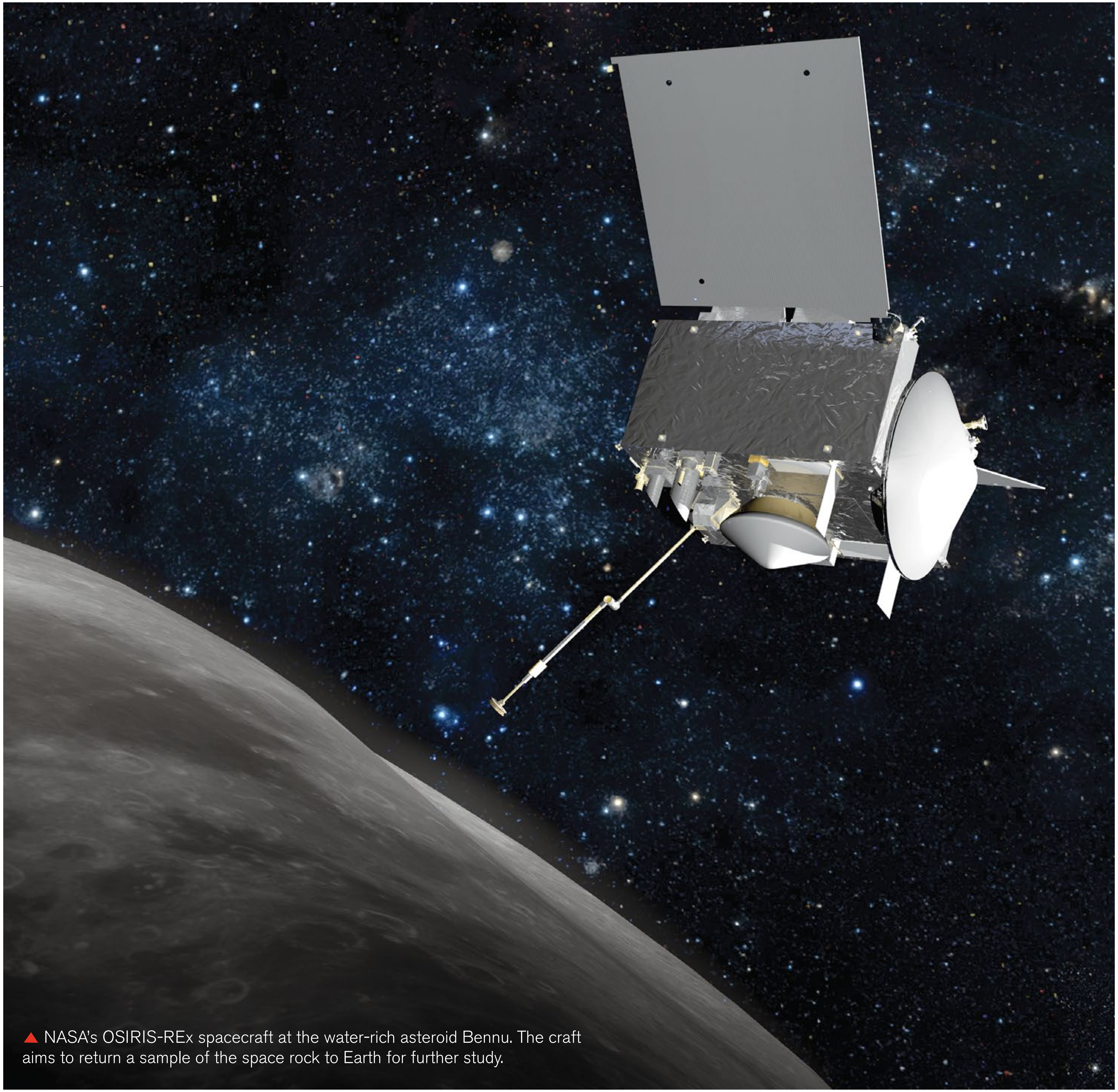
NEWS

Space Prospecting

A number of companies are getting closer to extracting resources from space rocks

The Outer Space Treaty (OST) turned 50 in December. The foundational 1967 pact establishes space as "the province of all mankind" and forbids the nearly 100 states that have ratified or acceded to it from colonizing celestial bodies or using them for military operations. The agreement is taking on renewed relevance with the looming prospect of asteroid mining—a possibility that was barely imaginable when the treaty was forged but is now a near reality.

Two companies, California-based Deep Space Industries and Washington State–based Planetary Resources, are actively working toward



▲ NASA's OSIRIS-REx spacecraft at the water-rich asteroid Bennu. The craft aims to return a sample of the space rock to Earth for further study.

NASA, LUNAR AND PLANETARY LABORATORY UNIVERSITY OF ARIZONA AND LOCKHEED MARTIN

extracting resources from asteroids. They aim to supply deep-space necessities such as water, rocket fuel and building materials, which are prohibitively expensive to transport from Earth. Both firms say they plan to launch prospecting spacecraft to asteroids by late 2020, with missions to test the technology in low Earth orbit to begin soon. Their ambitious timeline has full-scale mining operations planned for the latter half of the 2020s.

The easiest resource to target is water, says Deep Space Industries chief scientist John Lewis. The life-supporting liquid can be electrically converted into hydrogen and oxygen for fuel. Water makes up as much as 10 percent of the mass of some asteroids, locked up in minerals similar to the glittery mica found in many Earth rocks—but it can be baked out in a solar oven, along with other volatiles such as nitrogen or sulfur compounds. Modified terrestrial mining techniques could make it possible to harvest iron from asteroids as well.

To extract anything, though, companies will first need to gather raw materials from an asteroid—a process that some countries, including Russia, Brazil and Belgium, say runs afoul of the treaty. The OST makes no explicit mention of mining, but one of its key provisions is a ban on "national appropriation" of celestial bodies. That arguably applies to resource extraction, but the pact "doesn't provide you with much guidance" on that front, says Frans von der Dunk, a space law professor at the University of Nebraska–Lincoln.

▲ The United Launch Alliance Atlas V rocket, carrying NASA's OSIRIS-REx spacecraft, lifts off from Cape Canaveral, Fla., in 2016.

Proponents of asteroid mining, von der Dunk says, view the ban similarly to the "global commons" status of the high seas: no state may colonize the Atlantic Ocean, yet anyone can harvest its fish. Planetary Resources chief counsel Brian Israel and others similarly argue that using materials harvested from an asteroid would not constitute appropriation.

Several governments have embraced this permissive interpretation. The U.S. Department of State has held for decades that the OST permits commercial exploitation. The federal government doubled down in 2015, when President Barack Obama signed a law recognizing American citizens' property rights to asteroid-derived resources and authorizing a licensing program for mining. Luxembourg, which is angling to become a world hub for space mining, recently passed a similar law. By establishing national licensing regimes, Brian Israel argues, such laws fulfill the OST's requirement that states ensure the compliance of their citizens.

Not everyone is so sanguine, however. For other global commons, such as Antarctica, the guidelines for permissible extraction were spelled out in far more detailed treaties, notes Joanne Gabrynowicz, editor in chief emerita of the *Journal of Space Law*. Without such clarification, opponents of unilateral space mining claim that "because outer space belongs to everyone, the resources belong to everyone," von der Dunk says. Therefore, countries must agree on an "international licensing body and some international sharing of benefits" before private entities can mine. This argument resonates especially with developing countries, which see echoes of rich colonialists' history of invading foreign territories and exploiting their resources, Gabrynowicz adds.

But the prospects for a new international framework appear grim. The Moon Agreement, an earlier attempt at spelling out the rules for resource use, remains unratified by any major spacefaring country specifically because of concerns about mandatory benefit sharing, and the global appetite for new treaties seems meager. Von der Dunk hopes that "the rest of the world more or less aligns with the U.S. approach" over the next few years. But Stanford University research engineer Nicolas Lee predicts that nothing will happen until "a company actually goes out there and does something."

COURTESY OF NASA AND JOEL KOWSKY

That day may be closer than it seems. Lindy Elkins-Tanton, principal investigator for NASA's upcoming scientific mission to the metal asteroid Psyche, says previous missions have demonstrated all the technology needed to nestle against—if not land on—an asteroid. And NASA's OSIRIS-REx spacecraft is already en route to the water-rich asteroid Bennu, aiming to return a sample of the space rock for scientific study. OSIRIS-REx principal investigator Dante Lauretta, who also consults for Planetary Resources, believes almost all of the mission's technology will translate to commercial enterprise. Meanwhile the costs of space missions are plummeting thanks to the burgeoning private space industry.

There will still be a lag between the first missions and full-scale mining; Lauretta compares the current phase to "kicking over rocks to see where the gold nuggets are" and acknowledges that the technology for processing materials in space is not yet ready. But Lee is certain someone will pull off a mining operation sooner or later. When that happens, companies and regulators will have to find a healthy balance among many interests. "Exploration has not always been a positive thing in the past," Elkins-Tanton says. "We've got this opportunity right now to do better." *–Jesse Dunietz*

COURTESY OF NASA

Floating Treasure

A spacecraft has uncovered in lunar soil some traces of Earth's ancient atmosphere that were key to the development of complex life

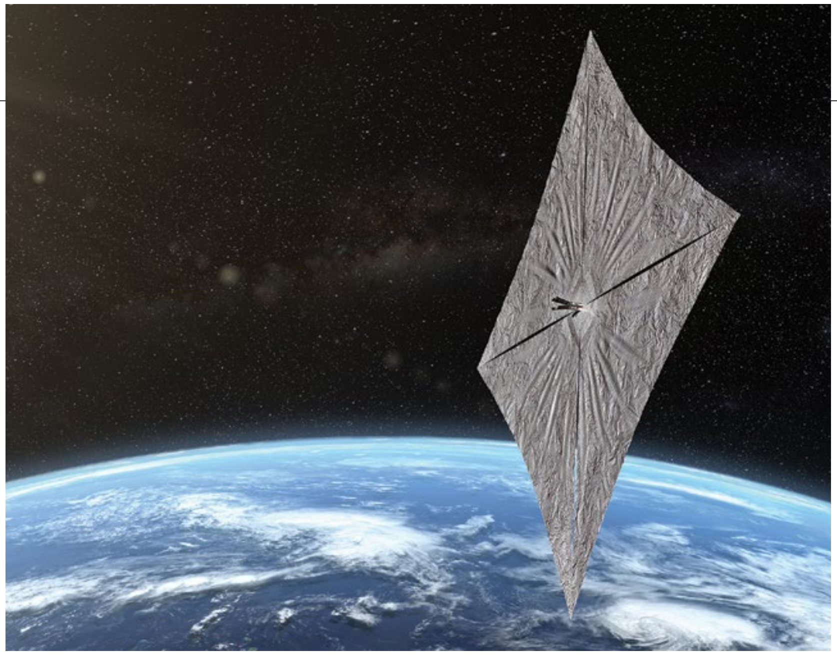
A Japanese spacecraft orbiting the moon recently made a surprising find: oxygen that came from Earth. Scientists think this oxygen could provide a historical record of our planet's ancient atmosphere.

Few reliable clues exist as to the early history of Earth's atmosphere and rocky surface because geologic activity has erased detailed evidence over time. Also wiped out are snapshot details that could be gleaned from meteorites made of material that formed around the same time and from similar material as Earth.

The discovery of terrestrial oxygen on the moon now suggests another way to get at the atmospheric history of Earth's first two billion years. The moon is constantly bombarded by a stream of highly charged particles emanating from the sun, called the solar wind. But for five days about every month our lunar neighbor is shielded by Earth's magnetosphere—a bubblelike region where the planet's magnetic field dominates. During this time, a window opens for slower oxygen ions from Earth to arrive at the moon. Scientists believe that these ions, which the SELENE spacecraft (better known as Kaguya) detected, drifted over geologic time from the outer layers of Earth's atmosphere and became embedded in the moon's regolith, a loose top layer of soil and rock. A team led by planetary scientist Kentaro Terada of Osaka University in Japan reported the result earlier this year in *Nature Astronomy*. "Our new finding is a direct link that ions from Earth's atmosphere are transported to the moon," where they could remain in the lunar soils for billions of years, Terada says.

This result excites scientists interested in a transition coinciding with the beginnings of photosynthesis in simple microbes, the planet's primeval life-forms. Somewhere around 2.45 billion years ago Earth's atmosphere changed from oxygen-poor to oxygen-rich under still mysterious circumstances that scientists call the Great Oxidation Event. Could some of the atmospheric oxygen produced at that time linger on the moon today? If scientists can collect and analyze samples of the terrestrial oxygen embedded in lunar soil, it could provide insights into how Earth's atmosphere has evolved over the eons.

In addition to trapped oxygen, the moon may harbor a trove of other evolutionary information about primordial Earth. "In principle, the moon has this remarkable collection of detritus from its sister planet," says astrobiologist Caleb Scharf of Columbia University, who was not involved in the new research. And that detritus might carry even more intriguing data. He adds: "It's not inconceivable that there are fossil organisms in Earth meteorites on the lunar surface." *–Saswato R. Das*



The LightSail 2 spacecraft will launch onboard a SpaceX Falcon Heavy.

Artwork showing a string of data encoded in clusters of qubits.

COURTESY OF JOSH SPRADLING THE PLANETARY SOCIETY (LEFT); EQUINOX GRAPHICS GETTY IMAGES (RIGHT)

Sailing on Sunshine

The privately funded LightSail 2 spacecraft will make a test flight in Earth orbit

There are no gas stations in space. To send affordable, lightweight spacecraft on long-range missions, NASA and several aerospace companies are seeking ways to exploit the power of sunlight. Possibilities include reflective "sails" billowed by the sun's rays, as well as next-generation solar electric propulsion. In the near future a privately backed project called LightSail 2 plans to launch a lunch box–size craft into orbit, where it will deploy a Mylar sail about as big as two parking spaces. If successful, these technologies could propel future NASA missions to Mars and beyond.

Solar sails are not science fiction—in 2010 Japan's IKAROS probe demonstrated a proof of concept during an interplanetary mission to Venus. Proponents say the technology used in the planned $5.45-million LightSail 2 demonstration, funded by the nonprofit Planetary Society, could maneuver low-cost satellites called CubeSats in Earth orbit without fuel. LightSail 2's performance could also inform NASA's Near-Earth Asteroid (NEA) Scout solar sail mission, scheduled to launch in 2019.

"The real niche [for solar sails] is for very small payloads that have long duration [and] low thrust requirements," says Les Johnson, principal investigator for technology for the NEA Scout mission at NASA's Marshall Space Flight Center in Huntsville, Ala. Steady sunlight pressure—equivalent to less than one ounce of push per acre of sail—can gradually accelerate a small probe. And tilting the sail steers the spacecraft by changing the angle at which sunlight reflects off it, Johnson explains. The technology is ideal for relatively cheap missions with tiny payloads that can take their time, such as NEA Scout's planned reconnaissance of an asteroid.

By the time sunlight reaches the vicinity of Jupiter's orbit, it is too weak for most solar sail–powered missions. But Jeffrey Sheehy, chief engineer of NASA's Space Technology Mission Directorate in Washington, D.C., and Johnson agree that the technology could potentially pave the way for interstellar missions, in which powerful lasers could accelerate sail spacecraft to a tenth the speed of light or faster. One private effort, called Breakthrough Starshot, hopes to send such craft on a flyby mission to Alpha Centauri, the star system nearest Earth, within a generation. *–Jeremy Hsu*

Quantum Leaps

Advances in "qubit" design could lead to more powerful computers

Quantum computers can theoretically blow away conventional ones at solving important problems. But they face major hurdles: their basic computational units, called quantum bits or qubits, are difficult to control and are easily corrupted by heat or other environmental factors. Now researchers have designed two kinds of qubits that may help address these challenges.

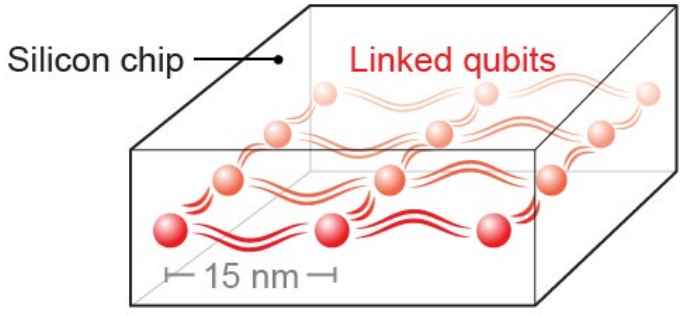
Conventional computer bits represent either a one or a zero. But thanks to an eerie quantum effect known as superposition—which allows an atom, electron or other particle to exist in two or more states, such as "spinning" in opposite directions at once—a single qubit made of a particle in superposition can simultaneously encompass both digits. When multiple qubits become "entangled" (referring to a quantum property that links one particle's actions to those of its partners), computing capacity can rise exponentially with the number of qubits. In principle, a 300-qubit quantum computer could perform more calculations at once than there are atoms in the observable universe.

Currently qubits based on a particle's spin direction must be positioned about 15 nanometers apart—any more, and their entanglement fails. But quantum engineer Andrea Morello of the University of New South Wales in Australia and his colleagues now claim to have designed qubits that can be separated by up to 500 nanometers. This provides much more room for vital apparatus to control the qubits. To create one of these so-called flip-flop qubits (see illustration at left), an electron is pulled some distance from an atom's nucleus. This causes the atom to exhibit positive and negative electric poles that can interact over relatively large distances, the researchers reported in September in *Nature Communications*.

Traditional Qubits

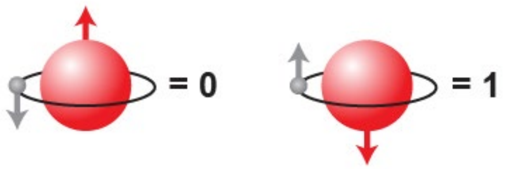
In traditional quantum computer designs, data are stored in the so-called spin state of either the nucleus or the electron of each atom.

These information-containing units, or qubits, can be magnetically linked to form a functioning computer only if the atoms are placed a mere 15 nanometers apart.

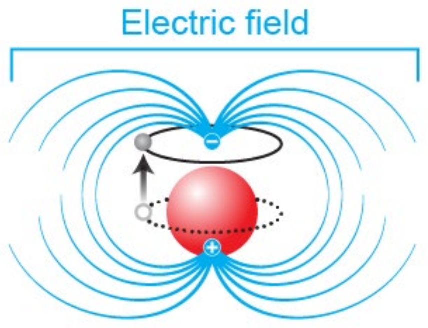


"Flip-Flop" Qubits

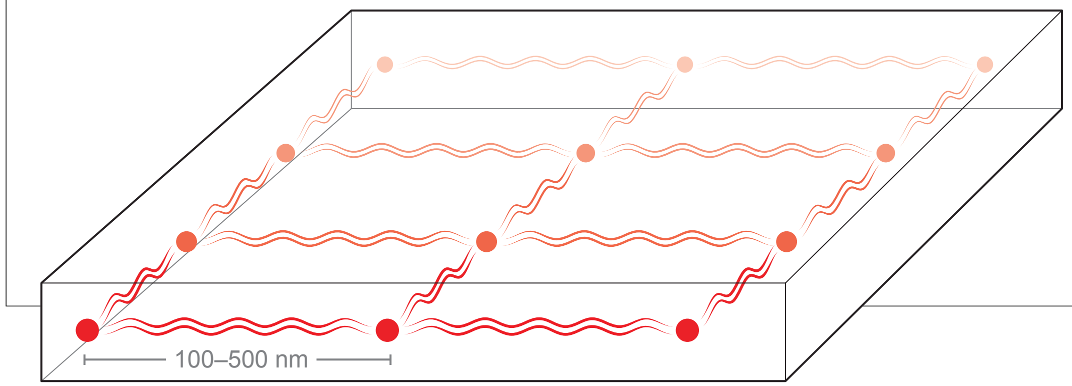
In the new "flip-flop" design, data are stored in the combined spin state of the nucleus and the electron of each atom. When the nucleus is "up," the electron is "down," and vice versa.



The electron is pulled away from the nucleus of each atom, creating an electric field that can extend over much longer distances than the magnetic fields used in previous designs.



With these long-reaching electric fields, qubits can be placed farther apart, making the physical construction of these minuscule devices much easier.



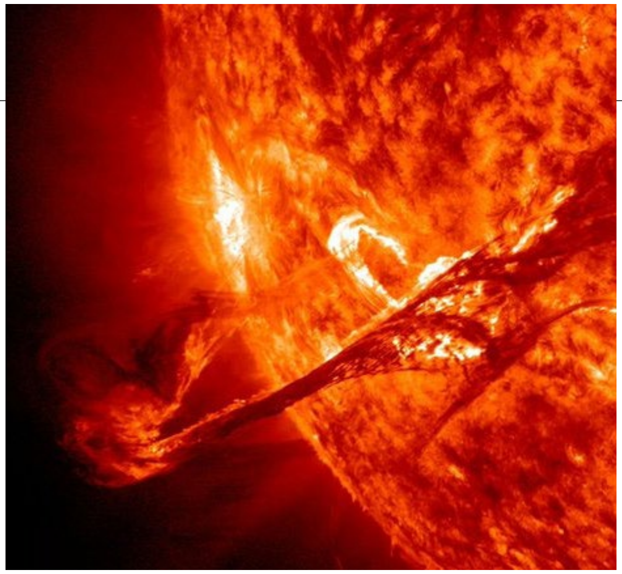
Another proposed qubit design is based on "quasiparticles," which are formed from negatively charged electrons interacting with positively charged "holes" in superconducting material. In work reported in August in *Nature*, scientists at the Delft University of Technology and Eindhoven University of Technology, both in the Netherlands, and their colleagues created structures in which a pair of separated quasiparticles can "braid," or exchange places, acting as a single qubit. The distance between them would decrease the chance that environmental effects could perturb both particles at once, which potentially makes such qubits highly stable, says study co-lead author Hao Zhang, a quantum physicist at Delft.

Both teams say they hope to create working versions of the new qubits soon. "I think it's very exciting that scientists are still pursuing new roads to build large-scale quantum computers," says quantum physicist Seth

Lloyd of the Massachusetts Institute of Technology, who did not take part in either study. *–Charles Choi*

Solar Storm Doomsday?

Space weather events could cost trillions of dollars in damage



▲ Solar flares such as this one from August 2012 could wreak havoc on electromagnetic systems on Earth.

COURTESY OF NASA, SOLAR DYNAMICS OBSERVATORY, AND AIA, EVE AND HMI SCIENCE TEAMS

Humanity has begun collectively grappling with the dangers of global threats such as climate change. But few authorities are planning for catastrophic solar storms—gigantic eruptions of mass and energy from the sun that disrupt Earth's magnetic field. In a recent preprint paper, two Harvard University scientists estimate the potential economic damage from such an event will increase in the future and could equal the current U.S. GDP—about $20 trillion—150 years from now.

There are precedents for this kind of storm. The so-called Carrington Event of 1859 began with a bright solar flare and an ejection of magnetized, high-energy particles that produced the most intense magnetic storm ever recorded on Earth. It caused brilliant auroras in the atmosphere and even delivered electric shocks to telegraph operators. But a Carrington-scale storm today would cause far more harm because society now depends so heavily on electrical power grids, communications satellites and GPS.

In an effort to quantify that threat, astrophysicists Abraham Loeb and Manasvi Lingam of the Harvard-Smithsonian Center for Astrophysics developed a mathematical model that assumes society's vulnerability to solar burps will grow in tandem with technological advances. Under this model (described in the paper, which was submitted to arXiv.org), during the next 50 years the potential for economic damage will depend primarily on the rising odds of a strong solar storm over time. Beyond 50 years our vulnerability will increase exponentially with technological progress until the latter levels off.

Some scientists question the model's predictions. “Estimating the economic impact is challenging now, let alone in over a century,” says Edward Oughton, a research associate at the University of Cambridge's Center for Risk Studies. Yet he warns that uncertainty should not deter us from practical preparations, such as making power grids more resilient and improving early-warning systems.

Loeb and Lingam envision a much wilder strategy: a $100-billion magnetic deflector shield, positioned between Earth and the sun. This idea seems “pretty preposterous,” however, given that solar particles arrive at Earth from all directions, says Daniel Baker, director of the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder.

A better understanding of “space weather”—the changing conditions in Earth's outer space environment, including solar radiation and particles—could help find the best strategies for confronting a dangerous solar storm, says Stacey Worman, a senior analyst at consulting firm Abt Associates. “This is a challenging but important question,” Worman says, “that we need more eyes on.” *–Jeremy Hsu*

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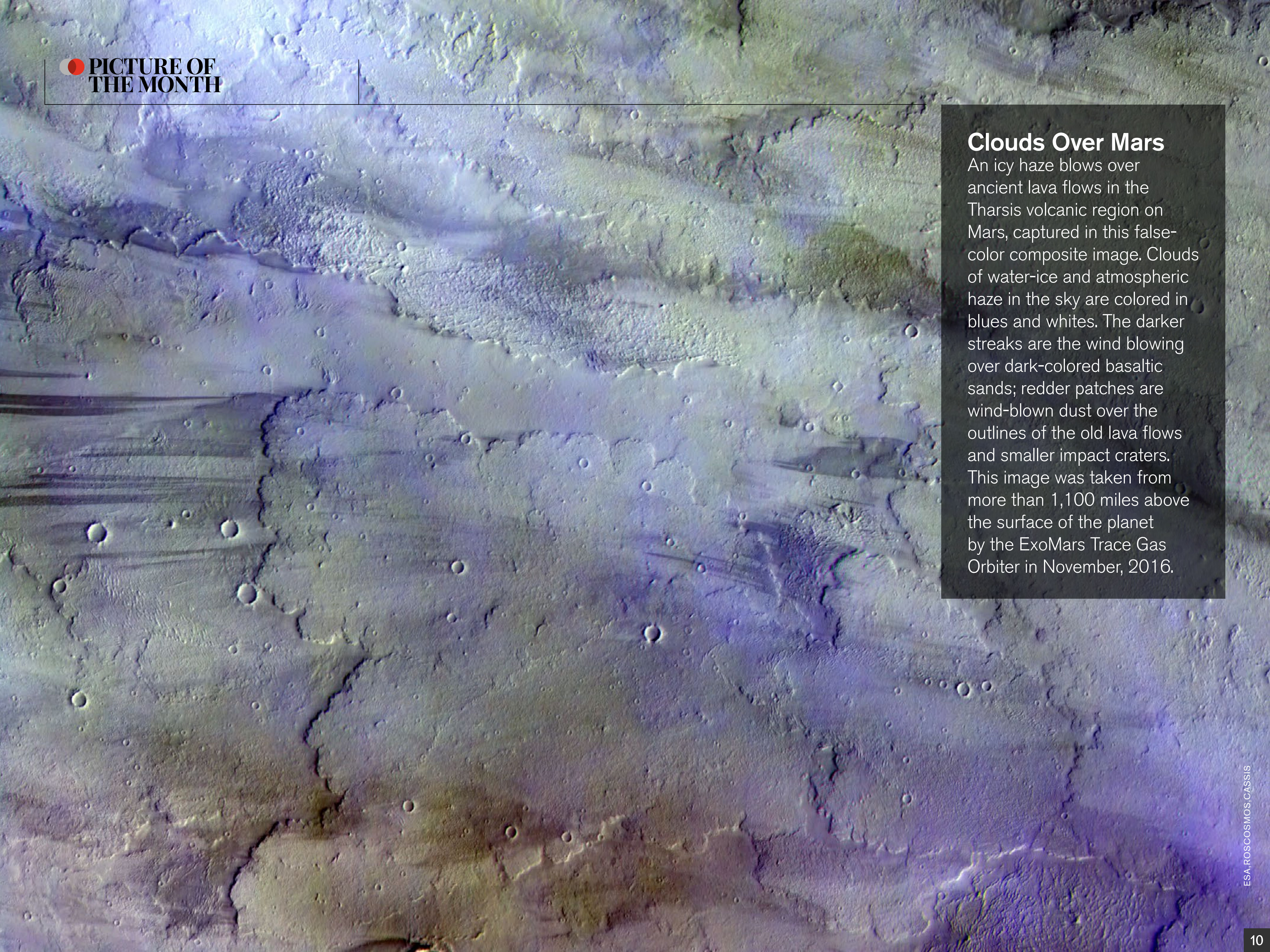


Clouds Over Mars

An icy haze blows over ancient lava flows in the Tharsis volcanic region on Mars, captured in this false-color composite image. Clouds of water-ice and atmospheric haze in the sky are colored in blues and whites. The darker streaks are the wind blowing over dark-colored basaltic sands; redder patches are wind-blown dust over the outlines of the old lava flows and smaller impact craters. This image was taken from more than 1,100 miles above the surface of the planet by the ExoMars Trace Gas Orbiter in November, 2016.

ESA,ROSCOSMOS,CASSIS

Nasa’s New Horizons changed everything we thought we knew about this distant Planet

PLUTO REVEALED

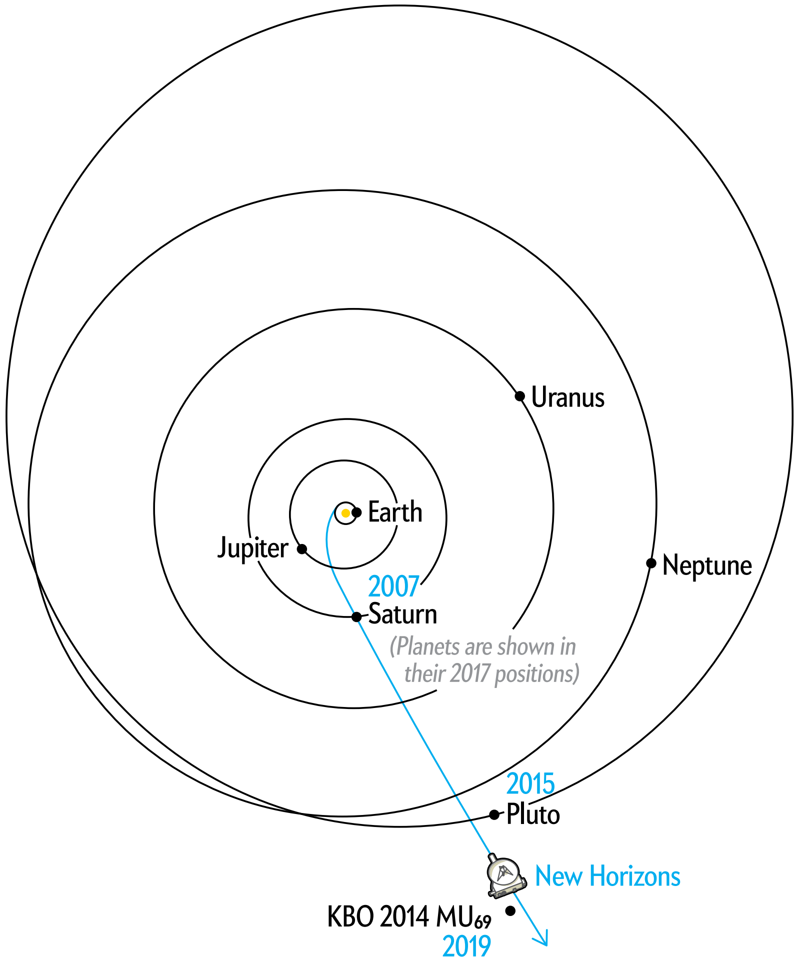
By S. Alan Stern

S. Alan Stern is a planetary scientist and associate vice president of the space science and engineering division at the Southwest Research Institute. He is principal investigator of the New Horizons mission and a former director of NASA's Science Mission Directorate.

PLUTO displays a huge variety of surface shades and features in this enhanced color view captured in 2015 by New Horizons.

COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE

AS THE CLOCK NEARED 9 P.M. ON JULY 14, 2015, I stood with then NASA administrator Charles Bolden and others in our mission control at the Johns Hopkins University Applied Physics Laboratory in Maryland. Within about a minute we were due to receive the first signals from the New Horizons spacecraft, some three billion miles away, after its daring, one-shot flyby of Pluto and its system of five moons.



That signal, racing at the speed of light to giant NASA antennas on Earth, would tell us whether or not the flyby had worked. Would it reveal that our mission had gone haywire or succeeded—or would there simply be silence? Anything was possible.

Nearby almost 2,000 invited guests also waited to hear the news. Across the world, so did countless others watching on television and online. It had taken more than 26 years to make this happen—14 years to "sell" the project, four more to build and launch it, and then more than nine years to fly it across the solar system. For myself as the project leader and for our mission and science teams, everything we had worked to achieve rode on what we were about to learn from the incoming signal.

Suddenly, communications arrived. Seconds later huge computer displays in mission control started decoding them into a spacecraft health report. One by one our flight engineers evaluated their data and reported in, every one of them confirming working spacecraft systems. New Horizons had survived its historic flyby and was operating perfectly. Cheers erupted across mission control, hands shot into the air to wave flags and hugs spread across the room. Our nearly three-decade quest to explore the farthest world ever reconnoitered—the Everest of planetary exploration—had succeeded!

By the next morning, New Horizons had already sent its first high-resolution images back to Earth, revealing Pluto as a stunningly complex world. Over the days and months that followed, the spacecraft's data continued to come in, and it kept coming until late 2016. All told, New Horizons made more than 400 separate observations using seven scientific instruments—a haul that produced about 5,000 times as much data as had the first mission to Mars, NASA's Mariner 4.

The scientific bonanza of that data set has revolutionized our knowledge of the Pluto system and upended common thinking about how complex and energetic small planets can be. And the viral public reaction to the mission—including more than two billion page views on our mission Web site, almost 500 newspaper front-page stories during the week of the flyby, along with dozens of magazine features, the Google doodle, and more—also came as a welcome surprise.

In hindsight, it is easy to see how valuable the exploration of Pluto has been—both for research and for the public's appreciation of planetary science. But truth be told, the mission almost never got off the ground.

IN BRIEF

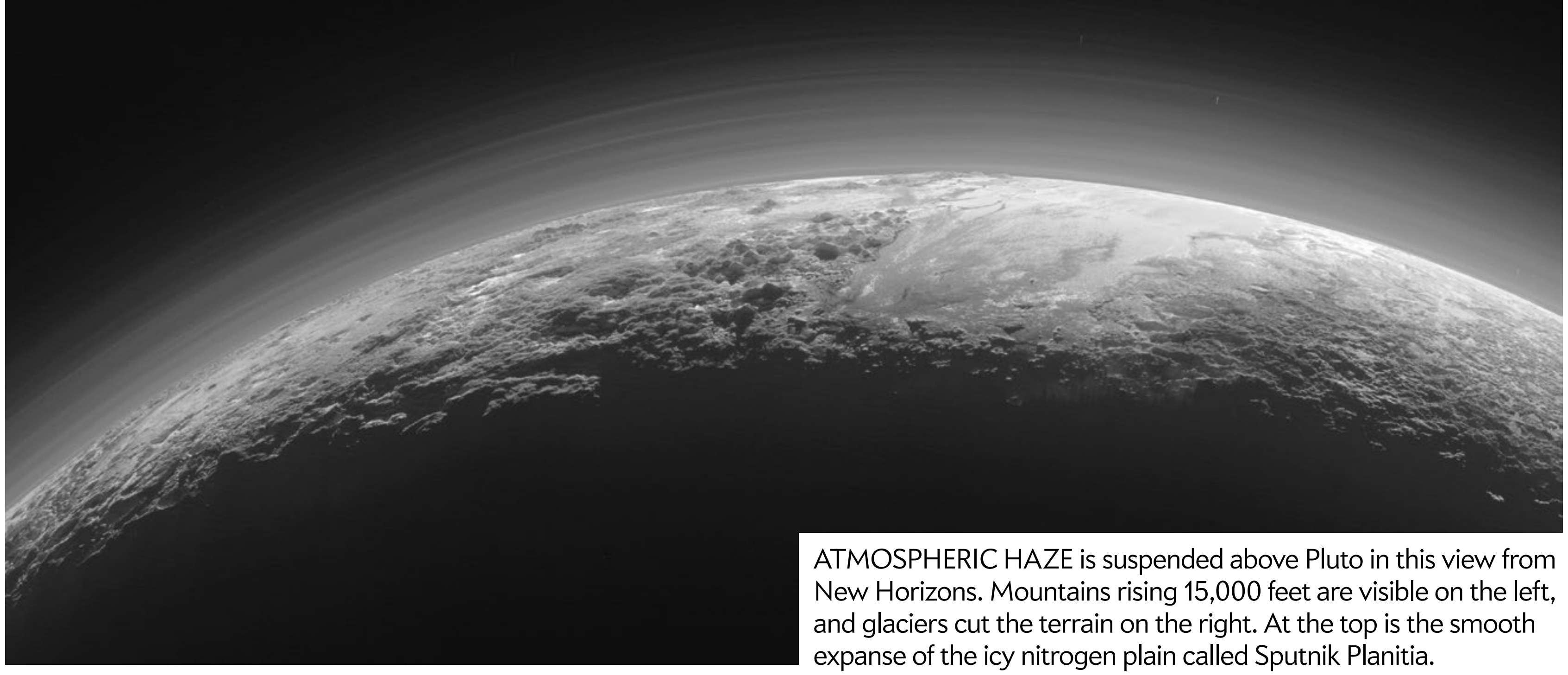
- **After a long** and rocky process to get the mission off the ground, NASA's New Horizons spacecraft launched in 2006 to explore the Pluto system close-up.
- **During a flyby** of the planet in the summer of 2015, the probe discovered that Pluto and its moons are far more complex and dynamic than expected.
- **Instead of a** static and featureless body, Pluto displayed towering mountains, vast glaciers and a surprisingly substantial atmosphere. Even on its moons, New Horizons found stunning features such as a red polar cap and canyons. Scientists are still analyzing the spacecraft's horde of data and expect many more discoveries soon.

2001: A SPACE ODYSSEY

NASA FIRST ANNOUNCED solid intentions to fly a mission to Pluto in 1999, when it invited teams around the country to propose instruments to fly on its Pluto Kuiper Express (PKE) mission. I led a team that submitted a main camera and spectrometer instrument suite proposal, but by September 2000 PKE's estimated cost had grown so high that before NASA could even select instruments to fly on it, the agency canceled the mission.

The planetary science community immediately swung into action, decrying the cancellation and asking NASA to reverse itself. The public also protested, inundating NASA with phone calls and more than 10,000 letters of protest. And one teenager even drove cross-country to appeal to NASA in person to resurrect the exploration of the ninth planet. (Despite common misconceptions, I, along with most other planetary scientists I know, refer to Pluto as a planet and do not use the International Astronomical Union planet definition, which excludes Pluto, in speech or research papers.) Finally, in December 2000, NASA announced that it would conduct a competition for new Pluto flyby mission concepts. Proposals would still have to meet the objectives set out for the PKE mission and must have a plan to reach Pluto by 2020, but they had to come in under roughly half of PKE's cost. Ultimately NASA received five phone-book-thick proposals from various teams, each offering detailed plans for such a mission. I led one of those teams. We called our mission New Horizons because we were proposing what would be NASA's first exploration of a new planet since the Voyager missions of the 1970s.

Our team, based at the Southwest Research Institute where I work and the Johns Hopkins University Applied Physics Lab where our spacecraft would be built and controlled, had much less experience with planetary missions than our main competitors, but we made up for that with ingenuity. To control costs, we suggested sending one, not two, spacecraft on the journey—something so risky it was almost unparalleled in first-time planetary exploration. We also proposed hibernating the spacecraft during the almost 10-year trip to Pluto to reduce staffing costs and concentrating on scientific capabilities at the expense of the ability to return data quickly after the flyby. We doggedly perfected our proposal and put it through countless reviews to ensure it was flawless in every respect—from technical implementation to science team composition to management plans, education and public outreach, cost controls and even contingency plans. In late November 2001 NASA announced that it had selected New Horizons over all our competitors. We had won! But little did we know what we were in for next.



ATMOSPHERIC HAZE is suspended above Pluto in this view from New Horizons. Mountains rising 15,000 feet are visible on the left, and glaciers cut the terrain on the right. At the top is the smooth expanse of the icy nitrogen plain called Sputnik Planitia.

COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE

To be ready to make our scheduled launch window in January 2006, we would have to design, build and test our spacecraft in just four years and two months—a process that had taken past NASA missions such as Voyager, Galileo and Cassini eight to 12 years to do. We would also have only 20 percent of Voyager's budget. But just as we were preparing to grapple with those challenges, less than three months after our selection, the Bush administration proposed canceling New Horizons altogether by writing it out of the federal budget released in early 2002. This move launched a protracted funding battle between Congress and the White House that was resolved only when the National Academy of Sciences rated Pluto exploration as a top "Decadal Survey" priority in summer of 2002, convincing enough lawmakers that the mission was worthy. Then, just as we thought we might be out of the woods, two multimonth shutdowns of Los Alamos National Laboratory jeopardized our ability to acquire enough plutonium to fuel our spacecraft's nuclear power generator.

Many people in NASA and the scientific community did not think the New Horizons team could survive so many setbacks. But we literally worked nights and weekends, 52 weeks a year, for four years, to overcome these hurdles. As a result, we made it to the launchpad on time, ready to fly to Pluto.

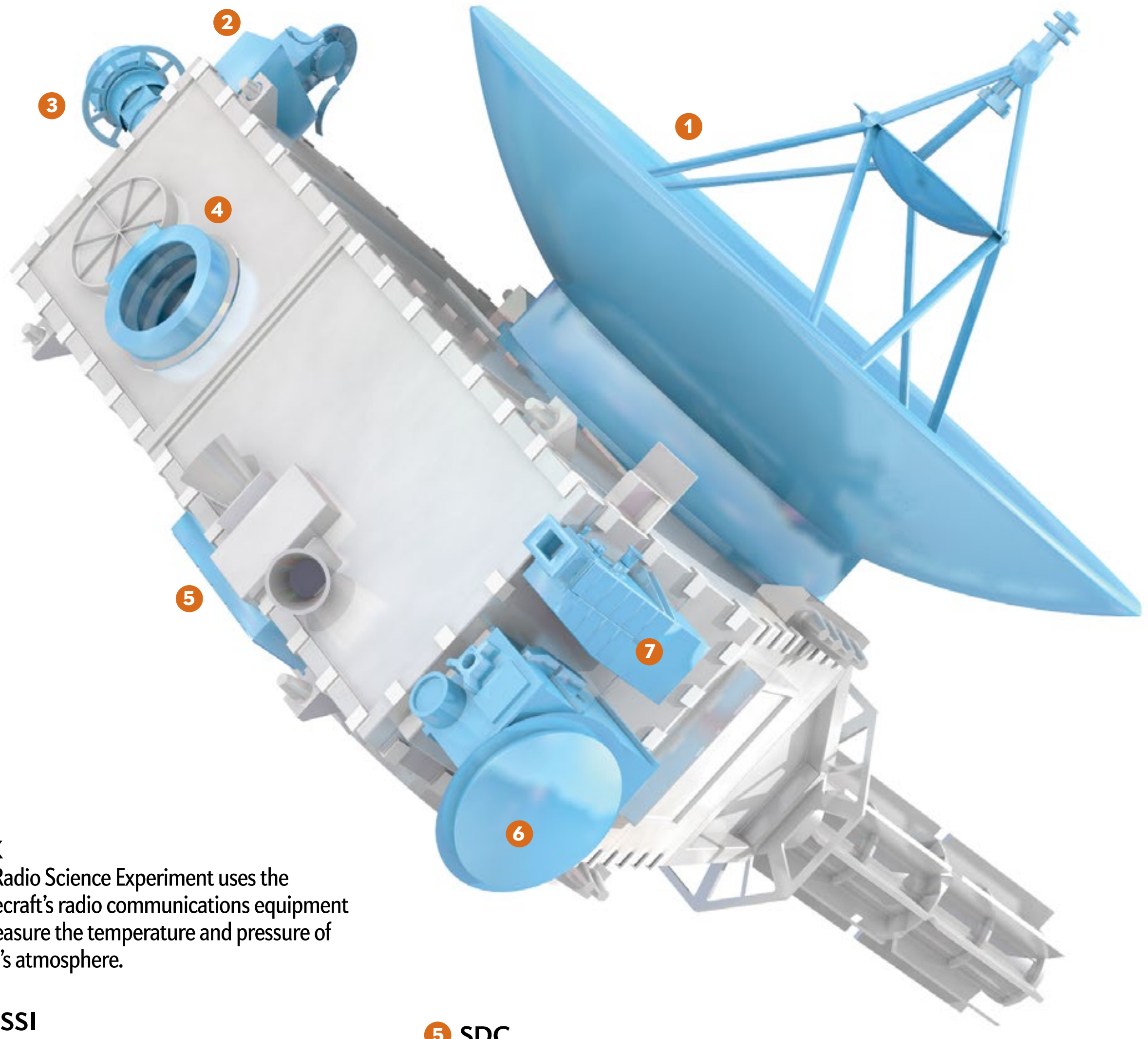
PLANNING A LONG-DISTANCE HOLE IN ONE

NEW HORIZONS WAS OUTFITTED with everything it would need to learn as much as it could during its brief flyby of the Pluto system. The business end of New Horizons is its seven-instrument payload. Included are black-and-white and color cameras, two spectrometers (which separate light into its various wavelengths to map the atmospheric and surface composition), and a detector to study the dust that impacts the spacecraft. Also onboard are two space plasma sensors used to measure how fast Pluto's atmosphere escapes and the composition of those escaping gases, as well as a radio science package capable of measuring surface temperatures and profiling atmospheric temperature and pressure with altitude.

This instrument payload brought more scientific firepower to bear on a first flyby of a new planet than ever

Eyes on the Horizon

New Horizons carried seven scientific instruments to collect as much information as it could about Pluto and its five moons during its brief flyby of the system. The suite of instruments allowed it to take color and black-and-white photographs, spectroscopic measurements and temperature readings, as well as detect the dust and space plasma the spacecraft encountered.



1 REX
The Radio Science Experiment uses the spacecraft's radio communications equipment to measure the temperature and pressure of Pluto's atmosphere.

2 PEPSSI
The Pluto Energetic Particle Spectrometer Science Investigation analyzes the density and composition of ions of plasma from Pluto's atmosphere.

3 SWAP
The Solar Wind Around Pluto instrument measures how fast Pluto's atmosphere is escaping and observes its interactions with the solar wind.

4 LORRI
The Long Range Reconnaissance Imager is a telescopic camera that can take high-resolution photographs at a distance. The data it collected helped scientists map Pluto and study the planet's geology.

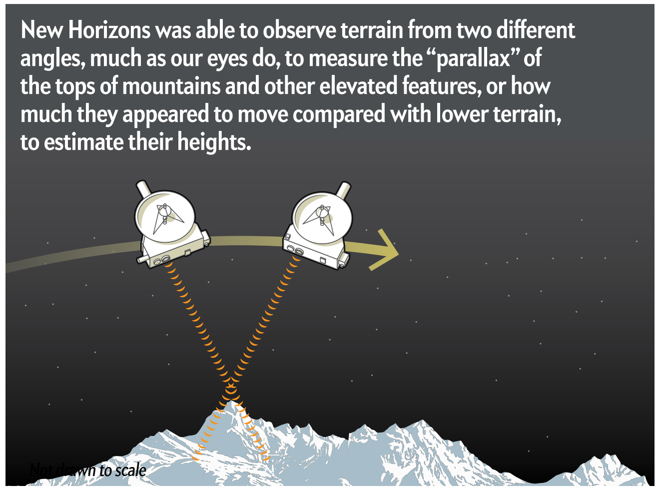
5 SDC
The Student Dust Counter, an instrument built and operated by students, analyzes the space dust that hits New Horizons as it voyages across the solar system.

6 RALPH
This camera and spectrometer measures the wavelengths of incoming visible and infrared light to make color, composition and thermal maps of Pluto's surface.

7 ALICE
Alice makes spectroscopic measurements of ultraviolet light to enable astronomers to study the makeup of Pluto's atmosphere and search for atmospheres around Charon and Kuiper Belt Objects.

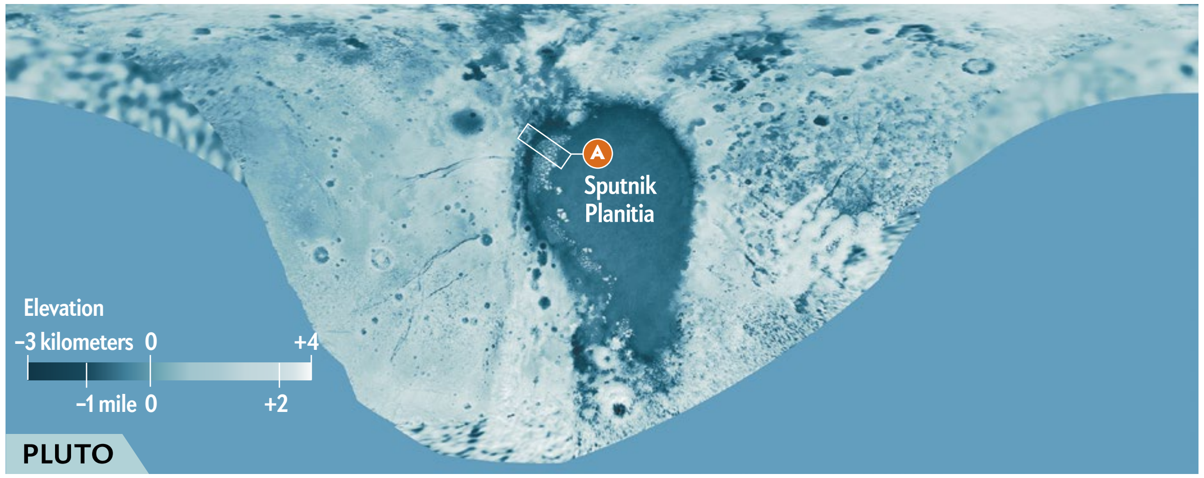
UNKNOWN TERRITORY

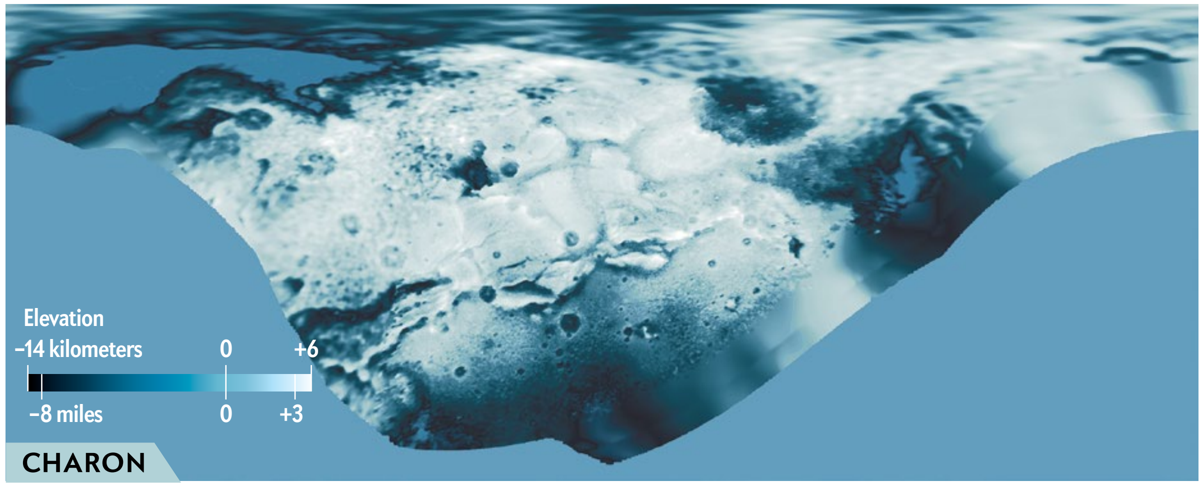
These global topographic maps of Pluto and Charon, made from New Horizons stereoscopic data, show the range of terrain on these worlds. Darker areas, such as Pluto's central Sputnik Planitia ice plain, represent lower elevations, and lighter regions are raised features such as mountains. Missing terrain in the bottom corners was either covered in darkness during New Horizons' flyby or was not resolved stereoscopically. The top photograph shows a 50-mile-wide strip on Pluto that displays rocky "badlands" (*on left*), rugged mountains (*center*) and the edge of the Sputnik Planitia glacier.



New Horizons was able to observe terrain from two different angles, much as our eyes do, to measure the "parallax" of the tops of mountains and other elevated features, or how much they appeared to move compared with lower terrain, to estimate their heights.

Not drawn to scale





*Courtesy of NASA, Johns Hopkins University Applied Physics Lab and Southwest Research Institute (*Pluto terrain*); NASA, Johns Hopkins University Applied Physics Lab, Southwest Research Institute, and Lunar and Planetary Institute (*elevation data*)*

Illustration by Bryan Christie Design

before, primarily because we were using 2000s-era technology, compared with earlier first-flyby missions built in the 1960s and 1970s, such as the twin Voyager spacecraft. For example, whereas the Voyager 1 surface composition mapping spectrometer had just one pixel, the composition mapper on New Horizons has 64,000 pixels. These advances in capability, combined with a spacecraft memory that can store more than 100 times as much data as Voyager's tape recorders, meant that New Horizons could be much more effective than previous first-flyby missions.

Although our spacecraft was "asleep" for much of its flight out to Pluto, planning for the flyby occupied our team for most of the journey. To accomplish its flyby objectives, New Horizons would need to arrive within a precise nine-minute window in time after its 9.5-year flight from Earth. It would also need to fly through a window in space that measured only around 35 by 60 miles. That might sound like a big target, but aiming to hit that window from three billion miles away at launch was the equivalent of hitting a golf ball from Los Angeles to New York City and landing a hole in one.

We also had to design, test and program every activity that we wanted New Horizons to carry out for the entire six-month-long flyby, which would run from mid-January through mid-July 2015. Those activities included more than 400 observations studying Pluto and all five of its moons by each of our seven scientific instruments; searches on approach for hazards and debris that could have harmed New Horizons; searches for new moons and rings; observations to triangulate on Pluto's position to help us home in on it; firings of our engines to ensure precise targeting of the flyby; and transmission of all the data recorded during the approach. We also had to plan not just one but three Pluto flybys, each along a separate trajectory, in case we found hazardous debris and needed to divert the spacecraft. Finally, we needed to write onboard intelligent software to handle more than 150 possible faults with the spacecraft or its instruments, and we had to create mission-control procedures for dozens of potential malfunctions too complex for the probe's software to deal with.

A NEW PLANET

BECAUSE OF ITS SMALL SIZE and distant orbit, Pluto was largely unknown to scientists before the New Horizons flyby. Even the Hubble Space Telescope could barely resolve its disk. About all that was clear was that it was roughly 1,400 miles in diameter, had at least five moons, a tenuous atmosphere, a reddish surface that contains ices of methane, nitrogen and carbon monoxide, and evidence of a polar ice cap and other large-scale surface markings. Those facts hinted it was likely to be more interesting and complicated than most of the frozen worlds in our outer solar system. But New Horizons revealed a planet that was far more complex, geologically diverse and active than most scientists anticipated.

Among our discoveries, we found that Pluto's atmosphere reaches hundreds of miles in altitude and has dozens of concentric haze layers but few, if any, clouds. New Horizons measured the atmospheric pressure at Pluto's surface for the first time, finding it is just 11 microbars—about the same pressure as at the top of Earth's mesosphere, some 50 miles overhead at the edge of space. We also found that Pluto's atmosphere is escaping 500 to 1,000 times less rapidly than expected, much more akin to the escape rates on Mars and Earth than the cometlike escape rates that preflyby models had predicted. And surprisingly, we found that Pluto's hazes tint its atmosphere blue, giving its skies a color distinctly reminiscent of Earth's.

New Horizons also revealed that Pluto is larger than most preflyby estimates had indicated, with a true diameter of 1,476 miles. This measurement definitively established Pluto as the largest of the small planets in the Kuiper Belt. Its larger size, when combined with Pluto's already known mass, lowered its density, meaning that while it is still a primarily rocky world with an icy exterior, the rock fraction is closer to 66 percent than the 70-plus percent we expected before the flyby. Of Pluto's remaining (nonrocky) mass, most is water ice, with just traces of more exotic ices on its surface. Models of Pluto's interior based on flyby measurements of its size, mass and shape now provide strong circumstantial evidence that Pluto hides a liquid-water ocean layer hundreds of miles down, where temperatures and pressures reach the water melting point.

For many years planetary scientists had debated whether Pluto's surface would contain steep topography. The answer depended on how deep its top layer of nitrogen ice was. This ice, which makes up most of Pluto's surface, is weak and slumps under its own weight, even in Pluto's reduced gravity, so a thick layer of it would prevent tall geologic features from forming. When New Horizons arrived at Pluto, though, some of its very first high-resolution images revealed mountains towering as high as 15,000 feet, suggesting that Pluto's surface nitrogen might be just a thin veneer over what we later identified as a water-ice crust.

New Horizons also revealed a stunning diversity of other geology on Pluto. We saw vast glaciers, fault systems running for hundreds of miles, chaotic and mountainous terrain caused by the breakup of gargantuan ice blocks, retreating methane scarps, methane snow caps on some mountain ranges, and thousands of one- to six-mile-wide pits presumably created by sublimating nitrogen ice across Pluto's equatorial plains.

Pluto's largest glacier, a nitrogen-ice feature named Sputnik Planitia (in honor of Sputnik, the first space mission), covers an area of more than 308,000 square miles—larger than the states of Texas and Oklahoma combined. No feature like it is known anywhere else in the solar system. Moreover, Sputnik Planitia is apparently geologically alive, as revealed by ice flows within it, as well as patterns across it that indicate that a heat source lies below. We also saw clear signs that its ices are being replenished by glaciers or avalanches from the surrounding mountain ranges that tower above it.

But Pluto's geologic surprises do not stop there. By counting its craters, we can estimate how long ago its terrain formed (the younger the surface, the less time there would have been for craters to build up). After doing this, we found a wide range of surface ages across the planet—from ancient, heavily battered ground more than four billion years old to middle-aged areas 100 million to a billion years old, to Sputnik itself, which has no identifiable craters and must be less—perhaps much less—than 30 million years old. This range of ages was unexpected because scientists widely predicted that Pluto's relatively small size would have caused it to cool early in its history and thus lose its ability to form new ground cover. As it turns out, that conventional wisdom was wrong. Pluto is still geologically alive today, although the sources of energy that power all this change are not yet clear.

Yet there was still more. Geologists on our team found methane-ice towers that climb more than 1,000 feet into Pluto's sky and stretch in an organized system over hundreds of miles. And if all that was not enough for one world, we also observed what appear to be large ice volcanoes only 100 million to 300 million years old, suggesting they operated in Pluto's recent past. Some on our team, myself included, see evidence for networks of drainage channels and a frozen lake that may indicate past epochs when Pluto's atmospheric pressure was much higher—higher even than Mars's today—allowing liquids to flow and even pool on the surface.

Simply put, Pluto's stunning range of atmospheric and surface features left the scientific community floored, suggesting that small planets can rival Earth and Mars in their complexity.

CHARON, Pluto's largest moon, has deep canyons and vast ice plains (1). Crowds cheer New Horizons' flyby at the Johns Hopkins University Applied Physics Lab in 2015 (2).

COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE (1); COURTESY OF BILL INGALLS NASA (2)

EXPLORING PLUTO'S SATELLITES

LIKE PLUTO ITSELF, Pluto's five satellites were largely unknown before New Horizons explored them. Charon, by far the largest of these worlds (at almost precisely half Pluto's diameter), was discovered by planetary astronomers Jim Christy and Robert Harrington using ground-based telescopes in 1978. Before New Horizons, it was known to be covered in inert water ice, to have little if any atmosphere, and to be much less colorful and reflective than Pluto. The four smaller moons—Styx, Nix, Kerberos and Hydra—were each discovered by members of the New Horizons team using the Hubble Space Telescope between 2005 and 2012. Scientists knew little about them before the Pluto flyby except their orbital properties, and they knew their colors were relatively neutral like Charon's. Even their sizes were only crudely estimated. None had ever been resolved by any telescope—they were simply points of light orbiting Pluto.

New Horizons allowed us to create detailed geologic, color, composition and topographic relief maps of Charon, to search much more sensitively for an atmosphere there, to measure its ultraviolet reflectivity, and to precisely determine its size and shape. The spacecraft was not able to fly as close to any of the four small satellites as it did to Charon, so what we could learn about them was necessarily less. But even so, New Horizons revealed their sizes, rotation periods and shapes and produced crude black-and-white maps of each. In the case of Nix and Hydra, New Horizons generated color maps, composition measurements and surface age estimates as well.

As a result of these discoveries, we now have a basic picture of Charon that rivals knowledge about the large icy satellites of the giant planets gathered by NASA's Voyager, Galileo and Cassini missions. Charon has no atmosphere at all and no surface volatiles, although we did find exotic ammonia- or ammonium-ice outcrops there. Based on crater counts, its surface looks to be more than four billion years old, with little variation in age, meaning that its geologic engine ran only briefly before exhausting itself. In that short time, however, Charon created vast, ice-flooded plains in its southern hemisphere, a vast belt of canyons up to five times deeper than the Grand Canyon, mountains and a red northern "polar cap" that is unlike any feature elsewhere in the solar system. That red pole seems to be made of methane and nitrogen that escaped from Pluto's atmosphere over time and was then redeposited at Charon's cold poles, where ultraviolet radiation chemically transformed these species into red hydrocarbon by-products. Charon's canyon belt appears to be the result of titanic stresses created by the freezing and expansion of water in Charon's interior as it cooled after the moon formed.

We found that Pluto's four small satellites are all about as reflective as Pluto, which is roughly twice as reflective as Charon; it is a mystery why they are so reflective when their surfaces seem to be made of the same material as Charon. None is large enough to retain an atmosphere. And although they each have some craters, which most likely created temporary rings around Pluto when material from the craters was ejected as they formed, we found that no such rings are present around Pluto today.

The orbits of Nix and Hydra suggest that they formed as a result of the same massive impact on Pluto that created Charon. Our maps of these moons have sufficient resolution to spot a variety of craters. Age dating of those craters reveals that their surfaces are about four billion years old—the same as Charon's. This finding proves that the impact that formed them occurred very early in the history of the solar system and cannot be the present-day energy source powering Pluto's current geologic activity. We also learned that the rotation periods of all four of Pluto's small moons are fast compared with their orbital periods—a surprising result that shows none of them has settled into the kind of tidal equilibrium of spin and orbit that is so common among the satellites of giant planets. Something, probably gravitational tugs from the binary system of Pluto and Charon orbiting each other, is affecting their rotation.

Although New Horizons has now transmitted all the data from its flyby of the Pluto system to Earth, we have still barely examined many aspects of its measurements. I expect many more scientific discoveries about Pluto's surface, interior, origin and atmosphere, as well as about its moons, as our science team and others begin the multiyear process of digesting this incredible data set.

NEXT: THE KUIPER BELT

NEW HORIZONS' EXPLORATION of the Pluto system is complete, but the spacecraft's mission continues. In 2016 NASA approved a five-year extension, running through mid-2021, in which the spacecraft will further explore the Kuiper Belt—the extended ring of small bodies and small planets that orbits the sun far beyond Neptune. The highlight of this exploration will be a close flyby of the small Kuiper Belt Object (KBO) 2014 MU_{69} on January 1, 2019. This ancient, reddish rock, preserved in a cosmic deep freeze far from the sun for more than four billion years, will be the most pristine leftover from the formation of the solar system ever to be explored. It is only about 19 miles across, yet it could have its own moons, and it is believed to be typical of the building blocks from which Pluto and other small bodies in the Kuiper Belt were formed.

New Horizons will encounter MU_{69} when its distance from the sun is about 44 times that of Earth. The spacecraft will use its full battery of instruments to study the object's composition and geology during the flyby. It will look for evidence of activity and an atmosphere, search for moons and rings, and take its temperature.

In addition to the close flyby of MU_{69}, New Horizons will study at least two dozen more KBOs between 2016 and 2021 from close range. These observations will allow us to place our MU_{69} results in context and search for satellites of these objects, study their surface properties and determine their shapes. New Horizons will also measure the properties of the space environment at the far reaches of the Kuiper Belt—studying the helium gas, solar wind and charged particles in this distant region of the sun's sphere of influence. We will also trace the density of dust in the Kuiper Belt out to a distance of 50 times the Earth-sun separation, just beyond the most extreme reaches of Pluto's elliptical orbit.

After 2021, we are optimistic that NASA will choose to extend New Horizons' mission even further. The spacecraft is healthy and has the fuel and power to continue operating and communicating with Earth into the mid-2030s or longer. During that period New Horizons can study many more KBOs and may even be able to make another close flyby of one.

FUTURE HORIZONS

AFTER A ROCKY DEVELOPMENT PERIOD and a long flight across the solar system, New Horizons completed the reconnaissance of the last of the planets known at the dawn of the space age and became the first mission to explore small bodies in the Kuiper Belt.

For 15 years as we planned and flew the mission, I challenged our science team to use all of the perspective and knowledge gained in the exploration of the other planets to predict what we would find at Pluto. As it turns out, nature surprised us, revealing a much more diverse and active planet than even we expected.

In fact, Pluto is so complex and so dynamic that many of us on New Horizons, and many more in the scientific community, would like to see another mission be sent to further explore it and its moons from orbit. We would also like to see more flyby reconnaissance missions such as New Horizons explore more of the bodies in the Kuiper Belt to study their diversity, just as spacecraft have done for the inner planets and the giant planets. We hope that the mission's stunning success is not the end but rather the beginning of exploring the planets and smaller bodies of the Kuiper Belt.

MORE TO EXPLORE

- The Pluto System: Initial Results from Its Exploration by New Horizons. S. A. Stern et al. in Science, Vol. 350, Article No. aad1815; October 16, 2015.
- Chasing New Horizons: Inside the First Mission to Pluto. Alan Stern and David Grinspoon. Picador, 2018.

The Neutrino Puzzle

The largest experiment ever to probe these mysterious particles could point the way to new physics

By Clara Moskowitz

Clara Moskowitz is Scientific American's senior editor covering space and physics. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science journalism from the University of California, Santa Cruz.

MARK ROSS STUDIOS

I’M STANDING ON A CATWALK IN A GIANT CAVE CRAMMED WITH INDUSTRIAL equipment, and I’m told that trillions of neutrinos are flying through every inch of my body each second. I reach out my arms as if to heighten the sensation, but of course, I can’t feel a thing. Nearly massless, traveling close to the speed of light, the ghostly particles traverse the empty space between my atoms without a trace. They also move mostly unimpeded through the hulking metal box that dominates the cavern. But a few times a day one will collide with an atom inside the school bus–size contraption, liberating charged particles that leave light trails visible to scientists. And these trails, physicists hope, will lead them into unknown territory.

The apparatus is part of the NuMI Off-Axis Electron Neutrino Appearance experiment, or NOvA, here at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill. A similar but larger detector is buried 800 kilometers away in Minnesota, where it catches neutrinos that have passed through this one and all the ground in between. NOvA, which has been operating since 2014, is the world’s longest-distance neutrino experiment, but it is laying the groundwork for something much larger—the Deep Underground Neutrino Experiment (DUNE). DUNE will start at Fermilab, where an accelerator will speed up and smash protons into graphite to create a beam of neutrinos. Those neutrinos will then fly through 1,300 kilometers of earth from Illinois to South Dakota. The additional 500 kilometers of travel should make it more likely that the neutrinos will display some of their trademark odd behavior.

DUNE is the most ambitious particle physics experiment to be attempted on U.S. soil since the failed Superconducting Super Collider (SSC) of the 1990s. The $1.5-billion project is scheduled to start up in the 2020s and should run for at least 20 years. But it is not just Americans who are excited—the project involves 1,000 researchers from 30 countries and counting. It will be the biggest neutrino experiment on the planet. It will also mark the first time that Europe’s major particle physics laboratory, CERN, has ever invested in a project outside the continent. Just as the Large Hadron Collider (LHC) discovered the famed Higgs boson in 2012, revealing the presence of a hidden field that fills the cosmos, scientists hope DUNE can use neutrinos to understand the universe on a deeper level. “We want to do for neutrinos what the LHC did for Higgs,” says DUNE’s co-spokesperson Mark Thomson, an energetic Brit from the University of Cambridge, who is helping to lead the charge on the experiment. “We believe we are on the verge of launching the next major revolution in particle physics.”

IN BRIEF

- **Neutrinos may** be the least understood fundamental particles that we know of. Chargeless and insubstantial, neutrinos rarely interact with other particles and were originally predicted to be massless. Now physicists know that they do have a small amount of mass, but the reason why is a mystery.
- **An ambitious project** under construction called the Deep Underground Neutrino Experiment (DUNE) will beam neutrinos 1,300 kilometers from Illinois to South Dakota. As they make the journey, the particles are likely to morph from one type, or flavor, to another, a phenomenon known as neutrino oscillation. By studying this peculiar behavior, physicists hope to elucidate the origin of neutrino mass and other quandaries.

Neutrinos stoke such extravagant hopes because they are the first particles to break from the so-called Standard Model, physicists’ best description of nature’s fundamental particles and the rules that govern them. The Standard Model, which explains the behavior of every other known particle with extraordinary precision, predicts that neutrinos should be massless. And that’s what scientists thought until about 15 years ago, when experiments in Canada and Japan discovered that neutrinos *do* have the slightest bit of mass. But neutrinos don’t seem to acquire mass the way other particles do. Instead, it appears, they come by their heft through so-called new physics—some particle, force or phenomenon that scientists have not yet found.

Over the past few years neutrinos have come to look like an ever more promising bridge to the future of physics because other attempts to reach that frontier have come up short. So far the LHC has failed to produce any particles not predicted by the Standard Model. Experiments designed to reveal the particles that make up dark matter, the invisible stuff that dominates the cosmos, have also come up empty. “We know the Standard Model is not complete—there are other things going on, but we don’t know what,” says Fermilab neutrino physicist Ste-

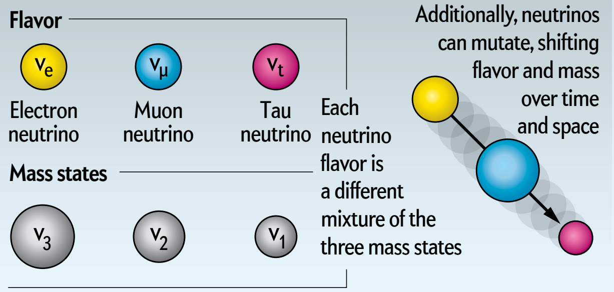
Perplexing Particles

Neutrinos are tiny particles that fly through matter at near light speed. They come in three types, called flavors. Weirdly, as they travel through space neutrinos that started out as one flavor can switch, or “oscillate,” into another. Scientists aim to investigate this strange behavior in the Deep Underground Neutrino Experiment (DUNE), the most ambitious neutrino project ever undertaken, due to start operating in the 2020s. Physicists will shoot a stream of neutrinos from the Fermi National Accelerator Laboratory (Fermilab) in Illinois to the Sanford Underground Research Facility in South Dakota and watch how many oscillate between flavors over the journey. Through this phenomenon scientists hope neutrinos will lead to a deeper understanding of physics.

NEUTRINO PRIMER

The three neutrino flavors—electron neutrino, muon neutrino and tau neutrino—are named after the particles they interact with—electrons, muons and taus. Neutrinos are not, as scientists once thought, massless. Because of the oddities of quantum mechanics, the flavors do not have definite masses; rather each flavor is a unique mix of three different “mass states.” The precise values of the mass states remain a mystery.

NEUTRINO PROPERTIES

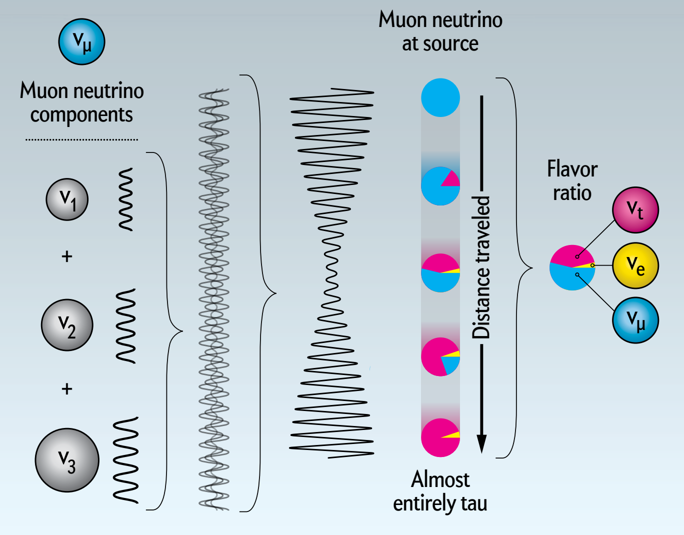


Each neutrino flavor is a different mixture of the three mass states

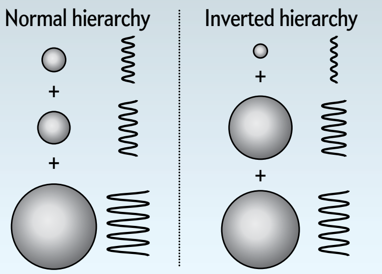
Additionally, neutrinos can mutate, shifting flavor and mass over time and space

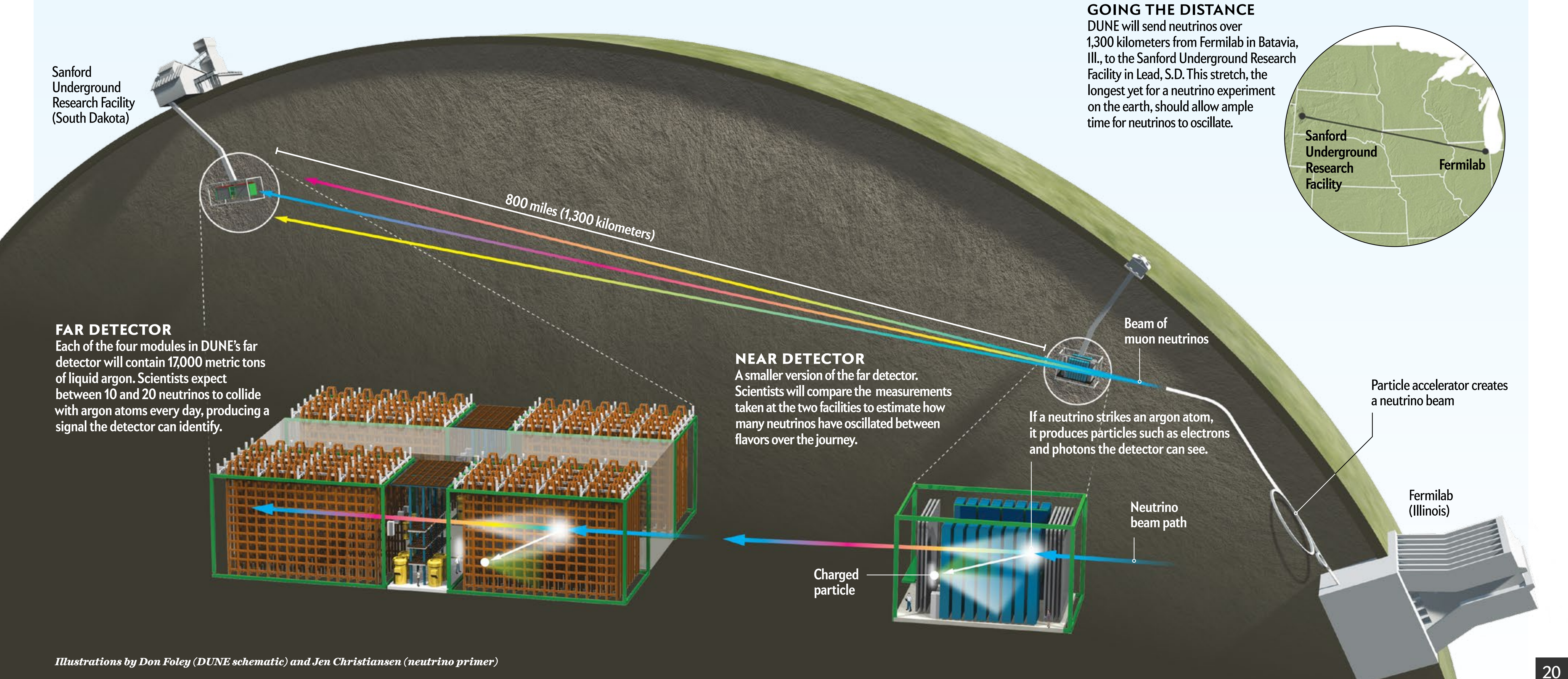
FLAVOR OSCILLATIONS AND THE ROLE OF MASS

As a neutrino moves through space, the different mass states of which it is composed travel at slightly different rates. Over time this lag causes the mix of mass states within a neutrino to change, and its flavor shifts accordingly. In this way, a neutrino that starts out as muon-flavored may turn into a tau or electron neutrino.



Scientists do not know the values of the three mass states, but theory suggests either that two are lightweight and one is relatively heavy (a configuration known as the normal hierarchy) or that one is light and two are heavy (the inverted hierarchy). DUNE should be able to determine which hierarchy is correct.





GOING THE DISTANCE

DUNE will send neutrinos over 1,300 kilometers from Fermilab in Batavia, Ill., to the Sanford Underground Research Facility in Lead, S.D. This stretch, the longest yet for a neutrino experiment on the earth, should allow ample time for neutrinos to oscillate.

FAR DETECTOR

Each of the four modules in DUNE’s far detector will contain 17,000 metric tons of liquid argon. Scientists expect between 10 and 20 neutrinos to collide with argon atoms every day, producing a signal the detector can identify.

NEAR DETECTOR

A smaller version of the far detector. Scientists will compare the measurements taken at the two facilities to estimate how many neutrinos have oscillated between flavors over the journey.

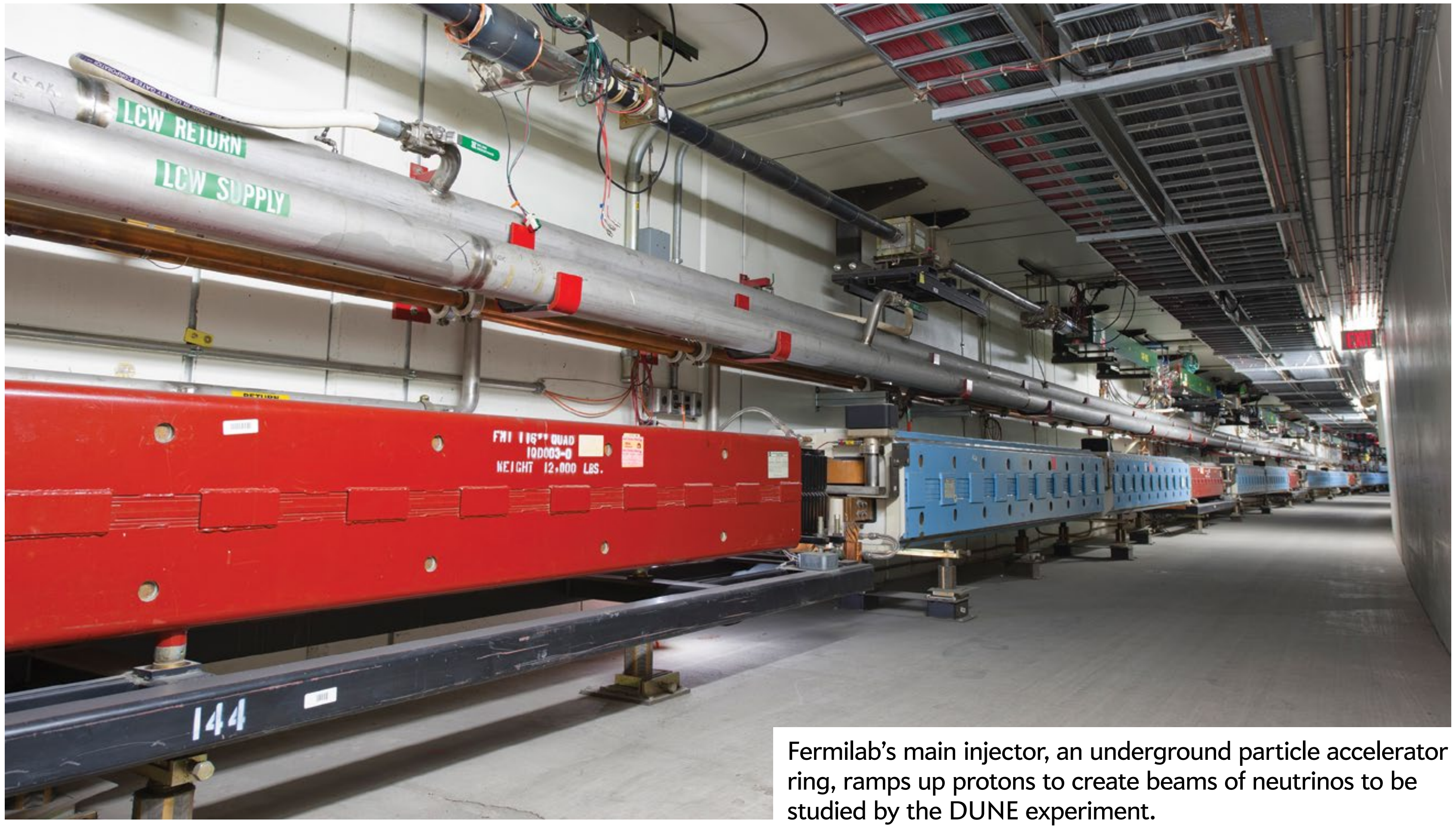
If a neutrino strikes an argon atom, it produces particles such as electrons and photons the detector can see.

Illustrations by Don Foley (DUNE schematic) and Jen Christiansen (neutrino primer)

phen Parke. “Some people are betting on the LHC with their careers. Others of us are betting on neutrinos.”

MASSIVE MYSTERY

THE DAY AFTER my visit to the NOvA cave, I find myself sitting in an empty office on the third floor of Robert Rathbun Wilson Hall, Fermilab’s main building. Parke, who is here along with theorist André de Gouvêa of Northwestern University, says he chose this room for our meeting because it was once the office of Leon Lederman, the retired former director of Fermilab, who developed a way to create a beam of neutrinos with a particle accelerator. That work, the bedrock of DUNE, revealed the existence of one of the three known types of neutrinos in 1962 and later won Lederman a Nobel Prize. Parke and de Gouvêa admit that although the field has come a long way since Lederman’s day, scientists are still puzzled. “The thing about neutrinos is, the more you understand, the more questions you have,” Parke says. “They’re very mischievous particles.”



Fermilab’s main injector, an underground particle accelerator ring, ramps up protons to create beams of neutrinos to be studied by the DUNE experiment.

COURTESY OF DEPARTMENT OF ENERGY AND FERMILAB

Parke, a native of New Zealand, got hooked on neutrinos shortly after coming to the U.S. for graduate school in the 1970s. In the subsequent decades, neutrinos lost their reputation as massless, boring particles. “There have been these revolutions one after the other,” he says. “The question is, Are there more revolutions out there?” He and de Gouvêa are betting yes. “We’ve only just begun to measure neutrino properties at a level comparable to other particles,” de Gouvêa says. “We don’t know their masses, there could be new [types of neutrinos], the neutrinos could talk to other particles that don’t talk to anybody else.”

DUNE will focus on neutrinos’ bizarre tendency to swap identities, a process called oscillation. The particles come in three varieties, or flavors: electron neutrinos, muon neutrinos and tau neutrinos. Researchers can tell them apart because when they interact with atoms in detectors, they produce different end products—electron neutrinos create electrons, muon neutrinos produce muons and tau neutrinos make tau particles (muons and taus are heavier cousins of electrons). Strangely, these three flavors are mutable. The particles might leave Fermilab as muon neutrinos and arrive in South Dakota as electron neutrinos. Or they might show up as tau neutrinos. As far as physicists know, neutrinos are the only particles that undergo this bizarre act of identity transformation.

When physicists discovered the shape-shifting tendency of neutrinos a decade and a half ago, it solved a long-standing mystery. In the 1960s, when scientists began studying neutrinos streaming out of the sun, they measured only about a third of the output predicted by theory. Oscillation explained why: the missing two thirds were morphing from electron neutrinos into muon and tau neutrinos as they traveled to Earth, but the instruments were set up to see only electron neutrinos. Although the discovery put to bed the so-called solar neutrino problem, it exposed another mystery: according to theory, the only way for neutrinos to switch flavors is for them to have mass—and that is something that the Standard Model did not predict.

The reason physicists know neutrinos must have mass is a head-scratcher that comes from quantum theory. For neutrinos to change flavors, each flavor must be made up of different “mass states.” Weirdly, each neutrino flavor does not appear to have a definitive mass; instead the flavors are a mix of three possible masses. (If that sounds strange, blame quantum mechanics, which tells us that particles are not definite entities but uncertain hazes of probability.) As neutrinos fly through space, the parts associated with each mass state travel at slightly different rates, a consequence of Einstein's special theory of relativity, which established that the velocity of a particle traveling near the speed of light depends on its mass. Over time this difference is thought to cause the mixture of masses in each neutrino to change, so a particle that starts out as, say, a muon neutrino, defined by its precise mass mixture, can turn into an electron or tau neutrino.

Scientists still do not know what the precise neutrino mass states are—only that they are different and nonzero. But by counting how many neutrinos oscillate during the journey from Illinois to South Dakota, DUNE aims to determine how the different neutrino masses compare with one another. Theory suggests that the three possible neutrino masses might be ordered so that two are very lightweight and one is heavy or, alternatively, that two of the masses are heavy and one is smaller. The first of these two options is known as the normal hierarchy, whereas the second arrangement is called the inverted hierarchy. DUNE should be able to distinguish between the two because the matter inside Earth is thought to affect neutrino oscillations; if the normal hierarchy were correct, scientists would expect to see different ratios of the three flavors than if the inverted hierarchy were right. "By firing neutrinos through matter, you can determine that difference very easily, and the farther you fire your neutrinos, the clearer your signal is," Thomson says. "That's a bit of physics that DUNE is absolutely guaranteed to nail within a few years."

THE ORIGIN OF MASS

ONCE THEY KNOW the ordering of the neutrino masses, researchers can tackle the larger question of how neutrinos get their mass. Most particles, such as the protons and neutrons inside atoms, acquire mass by interacting with the Higgs field; this field, which pervades all of space, is associated with the Higgs boson found at the LHC. But the Higgs mechanism works only on particles that come in both right-handed and left-handed versions, a fundamental difference related to the orientation of their spin relative to their direction of motion. So far neutrinos have been seen only in left-handed form. If they got mass from the Higgs field, then right-handed neutrinos must also exist. But right-handed neutrinos have never been observed, which suggests that if they are real they do not interact at all with any other forces or particles in nature—and that prospect strikes some physicists as far-fetched. Furthermore, if the Higgs field did work on neutrinos, theorists would expect them to have similar masses to the other known particles. Yet neutrinos are inexplicably light. Whatever the mass states are, they are less than one hundred-thousandth of the mass of the already puny electron. "Very few people think it's the Higgs mechanism that gives mass to the neutrinos," says Fermilab's director Nigel Lockyer. "There's probably a completely different mechanism, and therefore there should be other particles associated with how that happens."

> **"The thing about neutrinos is, the more you understand, the more questions you have."**
> *—Stephen Parke, Fermilab*

One possibility that excites physicists is that neutrinos could be Majorana particles—particles that are their own antiparticles. (This is possible because neutrinos have no electric charge, and it is a difference in charge that distinguishes a particle from its antimatter counterpart.) Theorists think Majorana particles have a way of getting mass without involving the Higgs field—perhaps by interacting with a new, undiscovered field. The mathematics behind this scenario also requires the existence of a very heavy set of neutrinos that has yet to be discovered; these particles would have up to a trillion times the mass of some of the heaviest known particles and would, in a sense, counterbalance the light neutrinos. For particle physicists, the prospect of discovering a new mass scale is enticing. "Historically we've always made progress by exploring nature at different scales," de Gouvêa says. And if some new field gives mass to neutrinos, maybe it affects other particles as well. "If nature knows how to do it to neutrinos, where else does it do it?" Lockyer speculates. "Theorists are asking: Could dark matter be a Majorana mass?"

DUNE will not directly test whether neutrinos are Majorana particles, but by measuring the mass hierarchy, it will help scientists interpret the results of experiments that do, which are going on now in Japan, Europe, the U.S. and elsewhere. Plus, DUNE should help elucidate the origin of neutrino mass by providing details about how neutrinos switch between mass combinations during oscillation. "We want to do the best possible neutrino oscillation experiment," de Gouvêa says, "because that's the one place where we know we're going to learn something about neutrino masses."

MATTER VS. ANTIMATTER

PROBING THE ODDITIES of these minuscule particles could also help solve a mystery of cosmic proportions: why the universe is made of matter and not antimatter.

Cosmologists predict the two should have existed in equal amounts after the big bang. Somehow, after most of the matter annihilated with most of the antimatter (as the two do on contact), there was a slight excess of matter left over. That matter makes up the galaxies, stars and planets that we see today.

To account for this asymmetry, scientists are on the lookout for a type of particle that behaves differently from its antimatter counterpart, and various clues, including hints seen at other experiments, point to neutrinos. DUNE will search for signs of so-called CP (charge parity) violation—in other words, evidence that antineutrinos oscillate from flavor to flavor at different rates than neutrinos. For example, theory suggests that DUNE might see antimatter muon neutrinos turning into electron neutrinos at anywhere between half to twice the rate at which matter neutrinos make this transition—a difference that Parke calls "enormous" and that could explain why matter won out in that initial battle. (Bizarrely, neutrinos could still oscillate differently from antineutrinos even if the two turn out to be same thing—in other words, if neutrinos are Majorana particles. In that case, the only thing separating neutrinos from antineutrinos would be their handedness, related to their direction of spin. Matter neutrinos, being left-handed, could act differently from antimatter neutrinos, which would be right-handed.)

DUNE will also be able to determine whether neutrinos come in only three flavors or whether there are more waiting to be discovered, as some theories speculate. The additional neutrino flavors would be so-called sterile neutrinos because they would not interact with normal matter at all. Earlier experiments, including the Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory and the Mini Booster Neutrino Experiment (MiniBooNE) at Fermilab saw inconclusive signs that an extra type of neutrino was interfering with oscillations, suggesting that sterile neutrinos exist that are heavier than the regular three. Researchers hope DUNE will either confirm or rule out that possibility. "Sterile neutrinos can change the pattern of oscillations we see at DUNE by quite a large amount," Thomson says.

BETTING BIG

TO ADDRESS ALL THESE QUANDARIES, scientists designed DUNE to collect far more data at far greater levels of precision than every previous neutrino experiment. The project will use a beam of neutrinos about twice as powerful as the strongest existing high-energy neutrino stream, and it will blast it at a detector that is more than 100 times larger than the biggest of its kind.

The centerpiece of the experiment will be the far detector to be installed in the Sanford Underground Research Facility in Lead, S.D. That machine will consist of four detector modules, each as long as an Olympic pool but six times as deep, that will be filled with 17,000 metric tons of liquid argon. When a neutrino strikes the nucleus of an argon atom in either the far or near detector, it will become, depending on its flavor, an electron, a muon or a tau particle. Muons will travel through the liquid argon in straight lines, kicking electrons out of argon atoms as they go, leaving a trail of electrons the detector can see. If the neutrino produces an electron, on the other hand, the process will create a photon that will then spawn two electrons, and then more photons, and so on, in a cascade of new particles. Tau neutrinos, likewise, would result in tau particles but only if the initial neutrino was energetic enough; taus, being more massive than electrons or muons, take more energy to create. Scientists at CERN will begin testing miniature versions of DUNE's far detector in 2018. "These detectors, it's kind of like a space mission in that once you turn them on you really can't stop them and take them apart to fix things," says Joseph Lykken, Fermilab's deputy director. "Once you put the 17,000 tons of liquid argon in, it's just too hard to get it out."

To succeed, DUNE will have to overcome the political and funding hurdles that have killed large physics projects before. Last July, scientists and officials held a groundbreaking ceremony at the Sanford facility to mark the start of major excavation, which will take at least three years. Of course, plenty of excavation took place for the SSC, which was planned to be even bigger than the LHC. The SSC probably would have discovered the Higgs boson, but it was canceled in 1993 because of cost overruns and changing political tides. "You can go back in history and look at the Supercollider, and, boy, is that a sad story," Lockyer says. "The international nature of DUNE is such a step forward." Having commitments and funding from more than just one country should help DUNE avoid the SSC's fate. "I'll say it's definitely happening," Lockyer says. And then he catches himself: "But could it not happen? Yes." ■

MORE TO EXPLORE

- Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects. DUNE Collaboration. Preprint submitted January 20, 2016. Preprint available at https://arxiv.org/abs/1601.05471
- Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF. DUNE Collaboration. Preprint submitted January 22, 2016. Preprint available at https://arxiv.org/abs/1512.06148
- Deep Underground Neutrino Experiment: www.dunescience.org

Cassini At Saturn

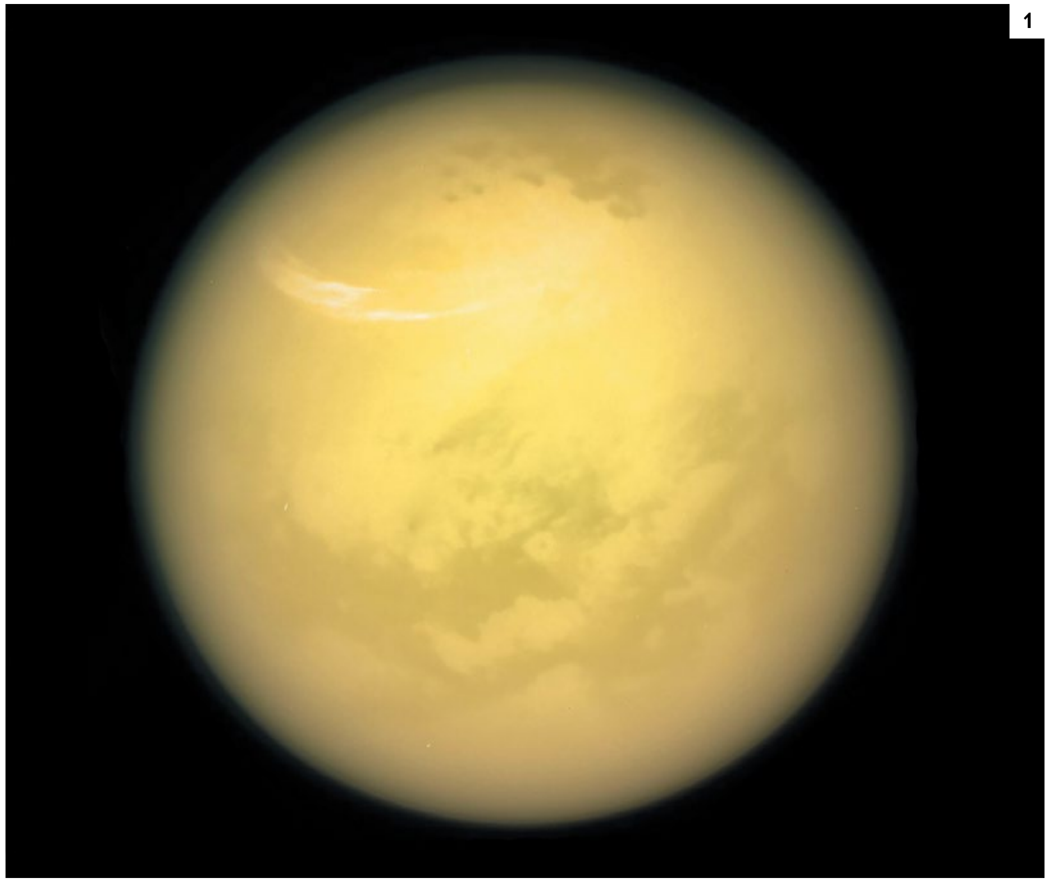
A historic exploration of the ringed planet, unprecedented in magnitude and spectacle, comes to an end

By Carolyn Porco

COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE

Carolyn Porco is a planetary scientist at the Space Science Institute in Boulder, Colo., and leader of the Cassini mission's imaging team. She is a visiting scholar at the University of California, Berkeley, and a member of Scientific American's board of advisers. This article was written, in part, while she was the science writer in residence at the Huntington Library, Art Collections, and Botanical Gardens in San Marino, Calif..

SOME EVENING WHEN SATURN IS HIGH IN THE SKY and the night is clear and dark, take a look through a backyard telescope. When you have had your fill of the planet's awe and beauty, search online for images that NASA's Cassini spacecraft has returned over the past 13 years in its travels around this ringed wonder. It will likely hit you hard: how far we have traveled, how proficient we have become as interplanetary explorers and how extraordinary an accomplishment it has been to come so intimately to know a world as distant as Saturn.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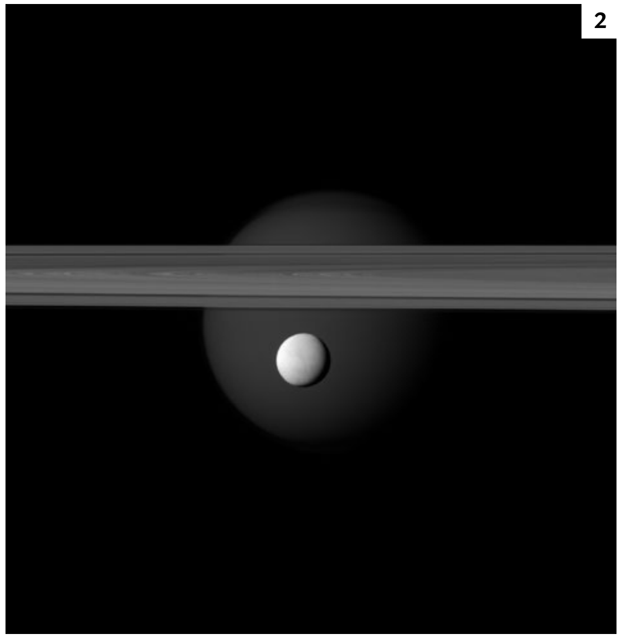
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TITAN, Saturn's largest moon, shines in a false-color image (1) and looms in the distance (2) behind the smaller moon Enceladus and Saturn's rings.

COURTESY OF NASA, JPL-CALTECH AND SPACE SCIENCE INSTITUTE (1); COURTESY OF NASA, JPL-CALTECH, SPACE SCIENCE INSTITUTE

Last September Cassini finished its travels around Saturn by diving, on command, into the planet's atmosphere. It was incinerated in a fireball ensuring that it will never accidentally hit and thereby contaminate any Saturnian moons that might harbor conditions suitable for life.

As the leader of the mission's imaging team, I, along with many of my colleagues on both sides of the Atlantic, began working on Cassini in late 1990, when it was still nothing more than an idea, a vision in the mind. I saw it through the planning and construction process, watched in person as the spacecraft launched on October 15, 1997, from Cape Canaveral, Fla., endured its seven-year voyage to Saturn and had a front-row seat as it arrived at its final destination in 2004. There and then Cassini began revolutionizing our view of Saturn and everything that surrounds it.

No mission has ever explored a planetary system as rich as Saturn's in such depth for so long. On its moon Titan, we found seas of hydrocarbons and a surface environment whose complexity rivals that of Earth. We observed the meteorology of Saturn's atmosphere and witnessed the birth, evolution and demise of giant storms. We saw new phenomena in Saturn's rings that told of the processes involved in the formation of solar systems, including our own. Like the cartographers of old, we mapped the moons of Saturn for future explorers and uncovered new ones, including an entire class of small bodies embedded within the rings themselves. And

IN BRIEF

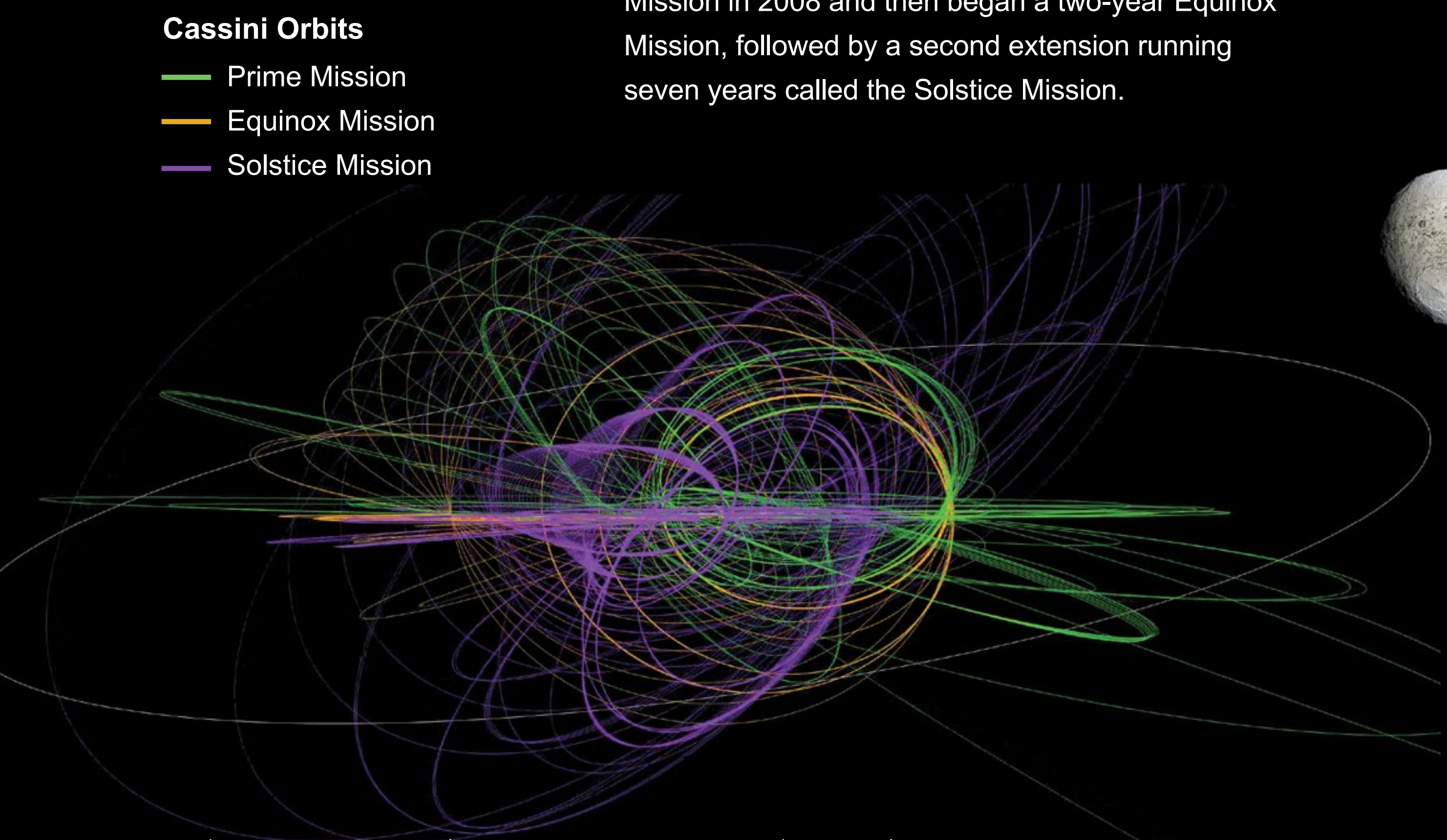
- **After 13 years** in Saturn's orbit, the Cassini spacecraft ended its mission in September 2017 by diving into the planet's atmosphere.
- **Over the course** of its voyage Cassini surveyed Saturn's atmosphere, rings and moons in exquisite detail. In 2005 Cassini's Huygens probe descended to the surface of Saturn's moon Titan.
- **Among its many** discoveries, Cassini found liquid-methane lakes on Titan and a buried liquid-water ocean on the moon Enceladus that escapes to the surface via geysers. Scientists suspect this underground sea might be capable of hosting alien life.
- **Cassini also** uncovered mountainous waves of rubble and "moonlets" in Saturn's rings and an effect that turns its atmosphere blue in the winter.

13 Years at Saturn

With its fuel source dwindling, the Cassini spacecraft dove into the atmosphere of Saturn in mid-September after 13 years in orbit. Over the course of its mission the probe delivered unprecedented discoveries about the complex planet, as well as about its varied moons and rings. It revealed worlds where rivers of methane flow into vast lakes, where jets of ice crystals from an underwater ocean spew into space, and where a single storm can encircle a giant planet. Here are some highlights. *–Edward Bell*

SPACECRAFT

Since Cassini took up residence around Saturn on June 30, 2004, its 293 orbits of Saturn varied in size, orientation and angle to give it both up-close and panoramic views of many locales in the system. The spacecraft completed its four-year initial Prime Mission in 2008 and then began a two-year Equinox Mission, followed by a second extension running seven years called the Solstice Mission.

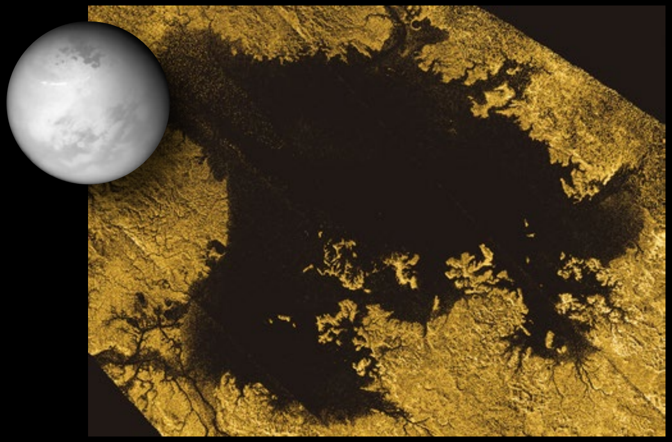


Ron MIller (Enceladus surface illustration)***; NASA,JPL-Caltech,ASI And Cornell*** (Titan surface)***;***
COURTESY OF NASA, JPL-Caltech and Space Science Institute (all other photographs)

MOONS

ENCELADUS

On this moon Cassini found towering geysers erupting from the south polar region, as seen in this artist's rendering. Evidence suggests they spring from a global subsurface water ocean that contains organic compounds and may be capable of hosting life.



TITAN

Saturn's largest satellite is the only place in the solar system other than Earth that has known stable liquid on its surface. Titan has many geologic and atmospheric processes similar to those on our planet, which generate methane rains that build river channels and form lakes and seas containing liquid methane and ethane. One lake is shown here in this false-color radar image from Cassini.

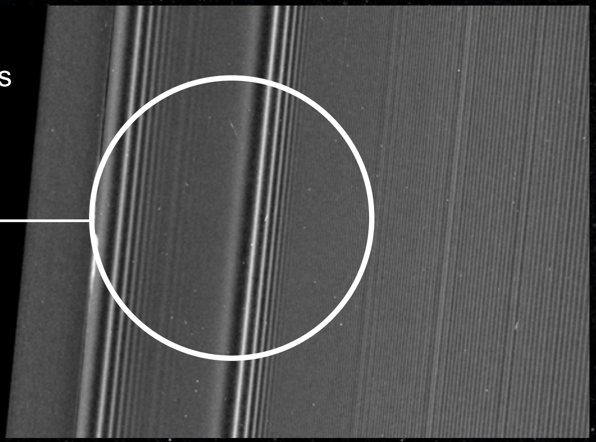
IAPETUS

This odd moon presented a mystery with its two-faced surface, which is half black and half white. Dark dust in Iapetus's orbital path lands on the leading face of the moon, and a thermal process transfers ice from the dark face to the light. This close-up image reveals that the same thermal process acts on small spatial scales as well.

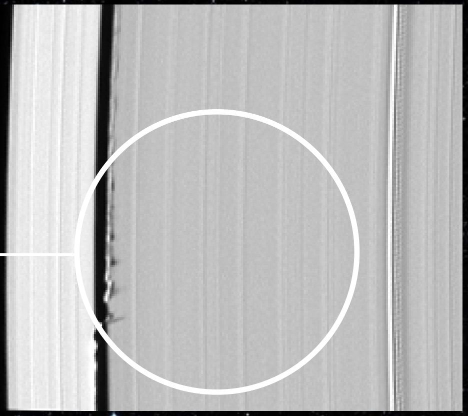
HYPERION

Cassini found this hamburger-shaped moon is pockmarked like a sponge. Scientists think that its unusually low density causes impacts to indent the surface rather than excavating it.

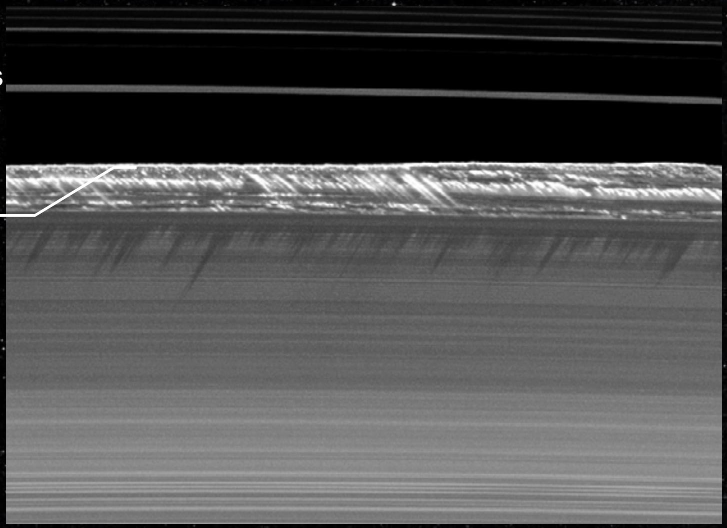
RINGS



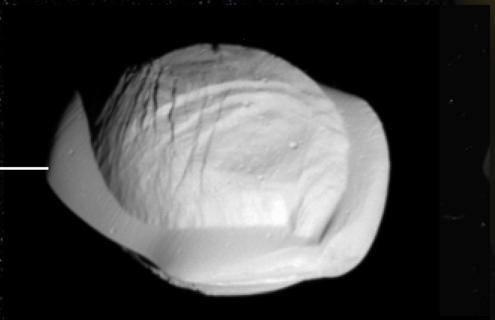
Cassini's close examination of Saturn's rings found that propeller shapes such as this one are gravitational disturbances caused by a moonlet too small to clear the area.



The tiny moon Daphnis, seen as a small dot in the Keeler ring gap, makes waves in the edges of the rings as it passes through.



A mountainous wall of ring rubble rises vertically in places 3.5 kilometers from Saturn's B ring and stretches at least 20,000 kilometers across.

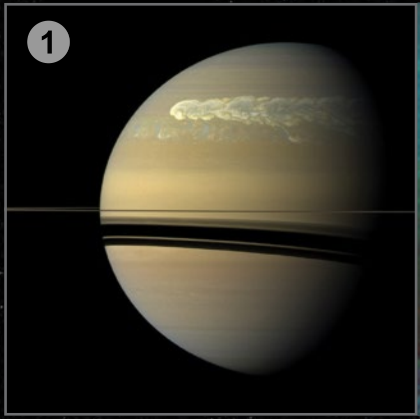


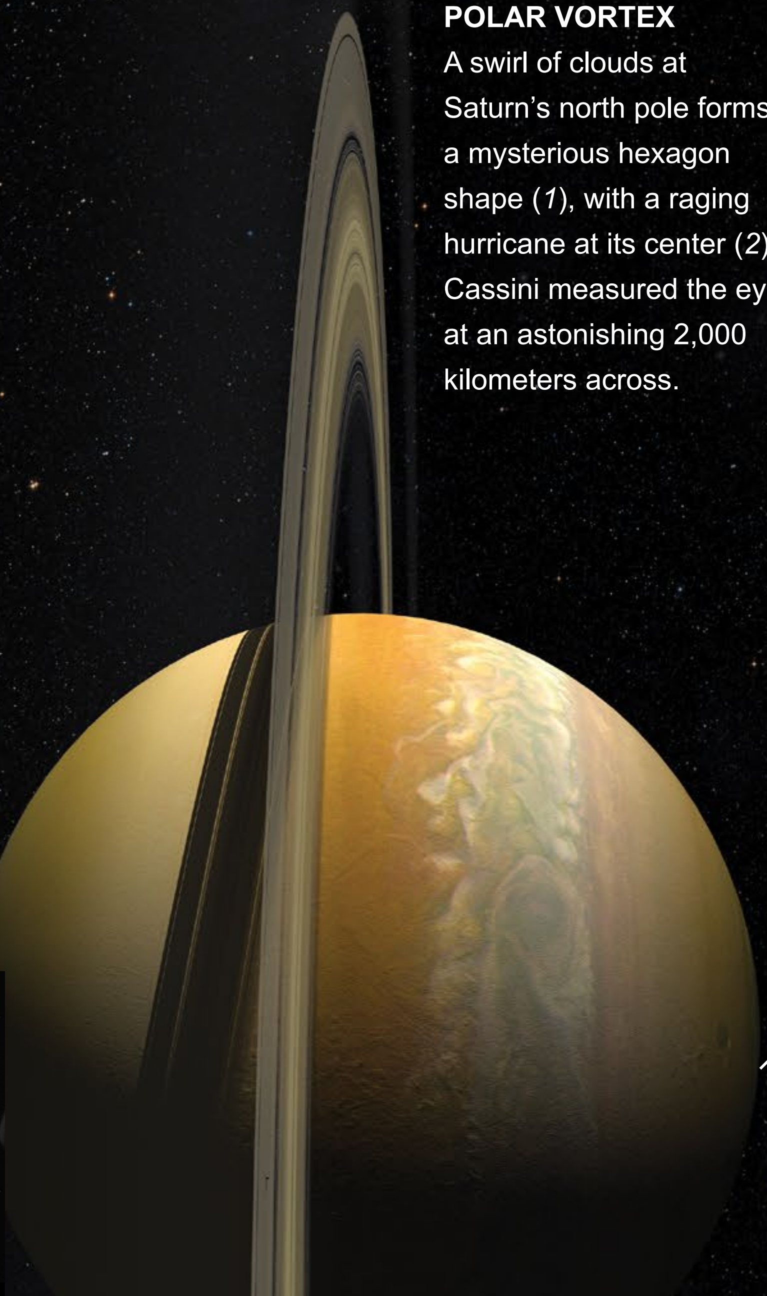
Pan, a 28-kilometer-wide moon in the Encke gap, got its cartoonish configuration from ring material falling onto it.

ATMOSPHERE

SUPERSTORM

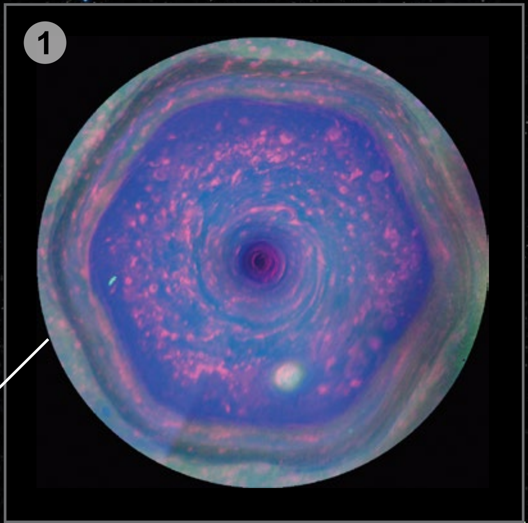
In 2010 Saturn's atmosphere erupted with an immense storm that began to spread around the planet (*1*). Within months this storm grew to encircle the globe, eventually meeting up with itself. Cassini imaged a false-color detail of the storm's various cloud layers (*2*).

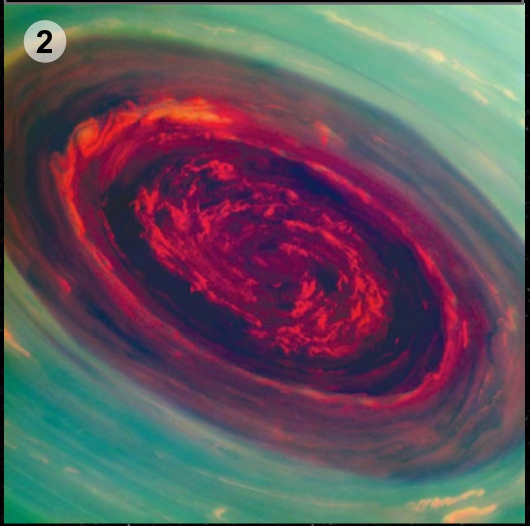




POLAR VORTEX

A swirl of clouds at Saturn's north pole forms a mysterious hexagon shape (*1*), with a raging hurricane at its center (*2*). Cassini measured the eye at an astonishing 2,000 kilometers across.





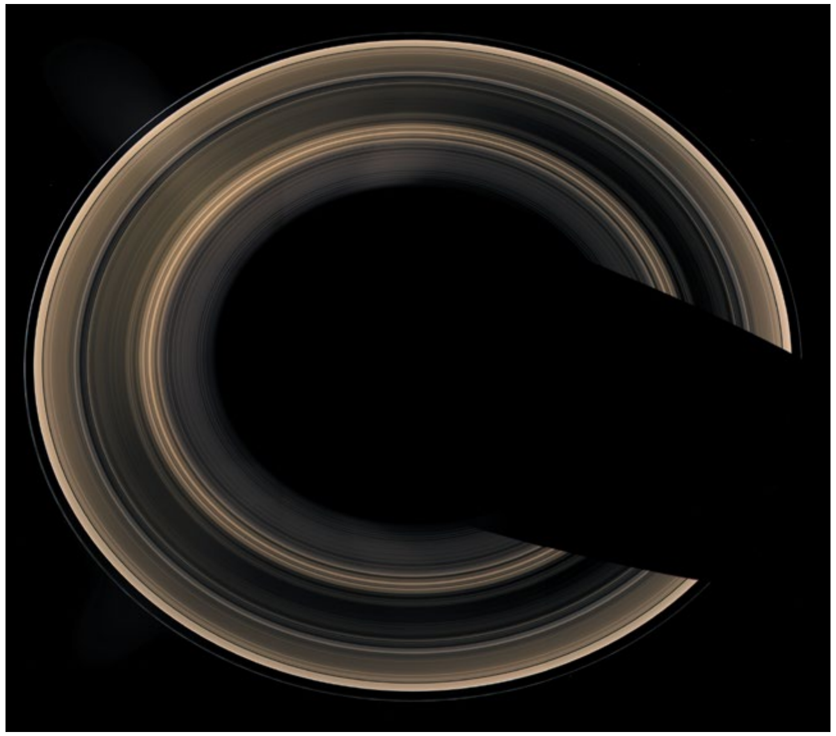
Edward Bell (Saturn vertical composite)
COURTESY OF NASA, JPL-Caltech and Space Science Institute (all other photographs)

then there is what I regard as Cassini's most profound discovery of all: at the south pole of the moon Enceladus, more than 100 geysers spouting from an underground ocean that could be home to extraterrestrial organisms. For 13 years my life has been lived out there in the outer reaches of the solar system. And now that bountiful scientific expedition has come to an end.

AN INTIMATE VIEW

THE NEED FOR A DETAILED, comprehensive examination of the Saturn system became clear during the early 1980s, after the two Voyager spacecraft made flybys of the planet. These celebrated events were the opening acts in the story of humanity's exploration of Saturn. They gave the planet dimension and personality but left behind questions that demanded answers. Voyager found Saturn to be a planet with a complex interior, atmosphere and magnetosphere. In its rings—a vast, gleaming disk of icy rubble—the mission recorded signs of the same physical mechanisms that were key in configuring the early solar system and similar disks of material around other stars. Voyager's passage through Saturn's inner system exposed diverse moons with dynamic forces at work. Titan, Saturn's largest moon, whose surface remained invisible through its thick, ubiquitous haze, nonetheless teased observers with hints of a possible ocean of liquid hydrocarbons. Altogether the Saturn system seemed an ideal destination for further in-depth study and exploration.

Cassini was an international undertaking, led by NASA and the European Space Agency and designed to be, in every dimension, a dramatic advance over Voyager. At the size of a school bus, it was bigger than Voyager and outfitted with the most sophisticated scientific instruments ever carried into the outer solar system. Cassini also carried the Huygens probe—a four-meter-wide, aerodynamically shaped device, equipped with a six-instrument payload, that descended to the surface of Titan.



SATURN'S RINGS are made of countless icy particles, some as big as houses, and contain gaps due to the gravitational tug of moons. Credit: Courtesy of NASA, JPL and Space Science Institute

After traversing the solar system, Cassini flawlessly took up residence around Saturn on June 30, 2004. Its trajectory around Saturn was both convoluted and precise, unfurling over the course of its 13-year tour like the opening petals of a blossom. To enable close-up viewing of everything in the inner Saturnian system, its orbits varied in size, tilt and orientation. We also had the luxury of modifying orbits to dive in for another look—in some cases, many looks—at things we had discovered earlier.

The length of Cassini's stay at Saturn was also critical to our success. Prolonged monitoring is the only way to catch unpredictable processes such as meteoroid impacts on Saturn's rings. Furthermore, the slow, steady orbital migrations of Saturn's moons, along with atmospheric changes that arise from the large seasonal variations in solar illumination, required us to collect observations over as lengthy a time span as possible. Cassini's nominal mission was four years long and slated to end on June 30, 2008. But the spacecraft's resounding triumphs in that time and the indisputable logic of keeping such a productive asset at work helped us press the case for continuing Cassini's mission. Our arguments were successful, garnering several extensions and ensuring, for example, that we witnessed the rare illumination conditions of Saturn's equinox in August 2009, when the sun's shallow rays on Saturn's rings revealed the presence of vertical structures protruding above the ring plane that cast long, easily seen shadows.

Ultimately Cassini's orbital operations ended nearly one half of a Saturnian year (or, on Earth, 13 years and two and a half months) after they began. We arrived a bit past the height of the planet's southern summer, and the mission will close at the height of its northern summer. This time frame allowed us to observe over almost a full seasonal cycle: we watched Saturn's and Titan's southern hemispheres go from summer to winter and their northern hemispheres go from winter to summer. It was somewhat of a cosmic cheat, but it worked.

THE MOONS

Before the space age, scientists thought the moons of the outer solar system would be featureless, geologically dead balls of ice. Voyager proved that assumption wrong; Cassini's mission was to survey Saturn's horde of satellites and return some understanding of their histories. In some cases, those histories turned out to be remarkable.

Take Iapetus. The origin of its two-toned appearance—one hemisphere as white as snow and the other deep black—was a long-standing mystery. From Cassini's high-resolution images, we learned that even on small scales, the moon is a piebald mix of dark and light patches. Together Cassini's cameras and thermal instrument showed us why this is so. Both the hemisphere-scale color variations and the local piebald patches are caused by a runaway thermal process found only on the slowly rotating Iapetus. Regions that start out dark get hot enough to sublimate ice and thus become darker and hotter. Regions

COURTESY OF NASA, JPL AND SPACE SCIENCE INSTITUTE

that start out white are colder and become the sites where those sublimated vapors condense. Over time all the ice in the dark region disappears and reaccumulates in the white regions. How did an entire hemisphere partake in this process? In its orbit around Saturn, Iapetus barrels through a cloud of dark, fine-grained material originating from Phoebe, one of Saturn's outer irregular satellites. This cloud turns Iapetus's entire leading hemisphere dark, keeping it warmer and ice-free. Mystery solved.

Another standout moon is Titan. Cassini's visible and near-infrared cameras as well as its radar instrument were able to cut through Titan's haze. And, of course, the early 2005 descent of the Huygens probe through Titan's atmosphere for two and a half hours captured panoramic images and measurements of atmospheric composition, transparency, winds and temperature before the probe came to rest on the moon's surface. In all, what Cassini found on Titan was a world out of science fiction, where the scenery—landforms and clouds—are recognizable but made of unusual substances, where the look of the place is familiar but the feel is not.

Titan, we discovered, has lakes and seas made not of water but of liquid methane. At the moon's south pole, Cassini's high-resolution camera sighted such a liquid body close to the size of Lake Ontario (and hence named Ontario Lacus) amid a district of smaller similar features. Other Cassini instruments later verified that Ontario Lacus indeed holds liquid methane. We have since found many bodies of liquid methane of varying sizes; for some reason, they mostly inhabit the high northern latitudes. Radar observations have revealed craggy, rocky shorelines that resemble the coast of Maine. In contrast, the equatorial plains, where the Huygens probe landed, are dry and covered with dunes that continue for long stretches, interrupted here and there by higher ground, all the way around the moon.

The lakes and seas of liquid organics on Titan's surface have naturally raised speculation about whether they might contain life. But the surface temperature on Titan is exceedingly cold: −180 degrees Celsius. It would be surprising to find chemical reactions similar to those we believe are required for water-based biochemistry operating at such temperatures. But should we ever detect truly "alien" biochemistry thriving in methane, it would be a remarkable and historic find.

In my mind, though, the site of Cassini's greatest discovery is without question Enceladus, an icy moon a tenth the size of Titan. There Voyager had laid bare vast, surprisingly smooth stretches that told of a past marked by intense internal activity and maybe even a liquid-water layer buried below its icy shell—both on a moon seemingly too small for such phenomena.

The first inkling we had of any activity on Enceladus came early in the mission, in January 2005, when we discovered a plume of icy particles coming off the south pole. Our images were immediately made available to the public, and Cassini followers on the Internet pulsed with excitement. Very soon thereafter other Cassini instruments confirmed that the plume was indeed real. Cassini's operators responded quickly, altering trajectories to have a closer look. What we learned about Enceladus during that early part of the mission absolutely astounded us, but it was not until after 2008, when we received NASA's blessing to extend the mission, that we were able to devote significant time and resources to examining this fascinating place.

Enceladus, we now know, is a moon being flexed and pulled by the gravitational tidal forces of Saturn. This tidal energy produces more than enough internal heat to create a global water ocean, possibly as thick in places as 50 kilometers, buried under an outer layer of ice a few kilometers thick. More than 100 geysers spout from four prominent fractures in the south polar terrain, creating a plume of tiny ice particles and vapor that extends hundreds of

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kilometers above the surface. Most of the solid mass in this plume falls back to the surface, but a small fraction extends farther to form Saturn's diffuse but large E ring.

Cassini was able to fly through the plume a dozen times and analyze its material. We found that the particles seen in our images, which were droplets of ocean only hours earlier, bore evidence of large organic molecules and compounds that indicated hydrothermal activity similar to that observed at deep-sea vents on Earth's seafloor. They also indicated an ocean salinity comparable to Earth's. The vapor accompanying these particles was mostly water but contained trace amounts of simple organic compounds, as well as carbon dioxide and ammonia—all ingredients important for the sustenance and even origin of life.

Cassini's results point clearly to a subsurface environment on Enceladus that could contain biological activity. We now must confront the goose-bump-raising questions: Did this small icy world host a second genesis of life in our solar system? Could there be signs of life in its plume? Could microbes be snowing on its surface? No other body so demonstrably possesses all the characteristics we believe are necessary for habitability. It is, at present, the most promising, most accessible place in the solar system to search for life. And some of us are so enthralled by this possibility that we are designing return missions to Enceladus to find out.

THE RINGS

The rings, of course, are what make Saturn the glorious spectacle it is, and understanding their intricate workings was a major objective for Cassini. They are the natural end state of the collapse of a rotating cloud of debris, and as such, they are the closest analogue to the rubble disk we think provided the raw ingredients for our own solar system. They are also a model for the protostellar disks from which new solar systems are born and even for the billions of pinwheels of dust and gas we call spiral galaxies. Of all there was to study at Saturn, the rings presented the greatest scientific reach, extending from our local neighborhood to clear across the cosmos.

Through Cassini's measurements, we have come to understand the origin of most of the structure in the rings of Saturn. In certain places, we find that the gravitational handiwork of some distant orbiting moon has disturbed the orbits of ring particles, creating sharp edges or wave disturbances that propagate out in a spiral pattern. In others, where moons are embedded in the rings, gravity has nudged particles into beautiful structures. Pan, for instance, a roughly 30-kilometer-wide moon in the Encke ring gap, has done this to the particles in its vicinity; in turn, infalling ring material has reshaped Pan, making the moon look as if it were wearing a tutu.

In regions of the rings where particles are especially dense, we uncovered self-generating waves, with wavelengths ranging from 100 meters to hundreds of kilometers, propagating through the disk. These waves can reflect off sharp discontinuities in particle concentrations and interfere with themselves and one another, creating a chaotic-looking geography. And our understanding of ring structure now includes the gratifying confirmation of a prediction Mark Marley, now at nasa's Ames Research Center, and I made in 1993: that acoustic oscillations within the body of Saturn could also create features in the rings. In this way, Saturn's rings behave like a seismograph.

Cassini found its most stunning ring surprises during the time surrounding the August 2009 equinox. Along the sharp outer edge of the most massive ring (the B ring), we found an incredible 20,000-kilometer-long continuous string of spiky shadows betraying the presence of "ring mountains"—waves of particles extending three kilometers above the ring plane. These formations might result from the extreme compression of material passing around small "moonlets" that have been caught in the resonance at the ring's edge like rushing water splashing against a large cliff face on the shore.

In another revelation, we saw a very subtle, tightly wound spiraling pattern continuing without interruption for 19,000 kilometers across the inner C and D rings. Some meticulous sleuthing by Matt Hedman, now at the University of Idaho, and his colleagues revealed that an impact of cometary debris within the inner rings in 1983 likely forced all the ring particles in the impact region into tilted orbits; these orbits precessed like a top, the inner ones precessing faster than the outer ones. Since then, this disturbance has wound up ever tighter, creating a three-meter-high spiral corrugation pattern in the rings. This structure did not even exist during the Voyager flybys. The solar system, we have come to see, is a dynamic marvel, and in their myriad and fluid forms, Saturn's rings are an object lesson in the universality, scalability and endless complexity of gravity. No artist could do better.

THE ATMOSPHERE

Cassini has also investigated the makeup and behavior of Saturn's atmosphere in great detail, uncovering some unexpected features in the process. Its instruments were able to study Saturn's atmosphere at a wide range of altitudes, revealing its global circulation patterns, composition and vertical structure. The atmosphere is divided into wide bands like Jupiter's, although Saturn's bands are less obvious from the outside because of a thick layer of haze lying above the upper ammonia cloud deck. When Cassini probed below the haze and into the troposphere, it revealed that the width of Saturn's bands alternates with latitude: narrower ones are darker and coincident with rapid jet streams, and the wider bands tend to be brighter, aligned with jets that are slower and maybe even stationary, relative to the general rotation of the planet. Overall, Saturn's atmosphere seems fairly static over time—even the surprising hexagon-shaped jet stream over the north pole has changed little, Cassini showed, since Voyager first sighted it. We are learning that stability is a common feature of large-scale atmospheric systems in the giant planets: with no solid surface underlying the gas, there is no friction to dissipate atmospheric motions. Once started, they endure.

We were delighted to find, however, that Saturn's atmosphere is not totally unresponsive to the changing seasons. Above the clouds in the northern winter hemisphere, the planet was putting on quite the unexpected show when Cassini first arrived: it was blue! Because the two Voyager flybys occurred near an equinox and thus returned no views of winter, this extreme coloration came as quite a surprise. Our best guess is that the lower flux of ultraviolet radiation during the winter, along with the sun-blocking effect of the ring shadows on the winter hemisphere, reduces the production of the overlying haze. A clearer atmosphere means better opportunity for Rayleigh scattering, the process that turns our own atmosphere blue, and for methane in the atmosphere to absorb the red rays of the sun. The gorgeous sliver of azure that colors the winter hemisphere in our images of Saturn is, in effect, a slice of Neptune's atmosphere spliced onto Saturn's. Who knew?

One distinctive property of Saturn, which has been known for a century, is that on timescales of decades, it is prone to the eruption of colossal storms. So we were thrilled to greet one such storm in late 2010. Over a period of about 270 days, we watched this thundering, lightning-producing behemoth be born as a small disturbance in the northern hemisphere, then grow, spread clear around the planet until its tail met its head, and eventually fade. This was yet another phenomenon that no spacecraft had ever witnessed. We suspect that water, the constituent of Saturn's deepest cloud deck, can suppress convection in the lighter hydrogen atmosphere for a period of decades, until finally buoyancy wins out and a large convective outburst ensues.

SURVEYOR OF WORLDS

From its inception in 1990 to its final dramatic conclusion last September, Cassini has been a major, extraordinarily successful component of humanity's six-decade-long exploration beyond our home planet. Its historic expedition around Saturn has shown us intricate details in the workings of an alluring and remarkably alien planetary system. It has expanded our understanding of the forces that made Saturn and its environs, our solar system and, by extension, other stellar and planetary systems throughout the cosmos what they are today.

It is doubtful that we will soon see a mission as capable as Cassini return to Saturn. To have been part of this magnificent adventure has been to live the taxing but rewarding life of an explorer of our time, a surveyor of distant worlds. I sign off now, grateful in knowing that the story of Cassini is one that will inspire humankind for a very long time to come.

MORE TO EXPLORE

- Saturn's Curiously Corrugated C Ring. M. M. Hedman et al. in *Science,* Vol. 332, pages 708–711; May 6, 2011.
- Enceladus's Measured Physical Libration Requires a Global Subsurface Ocean. P. C. Thomas et al. in *Icarus,* Vol. 264, pages 37–47; January 15, 2016.
- Could It Be Snowing Microbes on Enceladus? Assessing Conditions in Its Plume and Implications for Future Missions. Carolyn C. Porco et al. in *Astrobiology.* Published online August 11, 2017.

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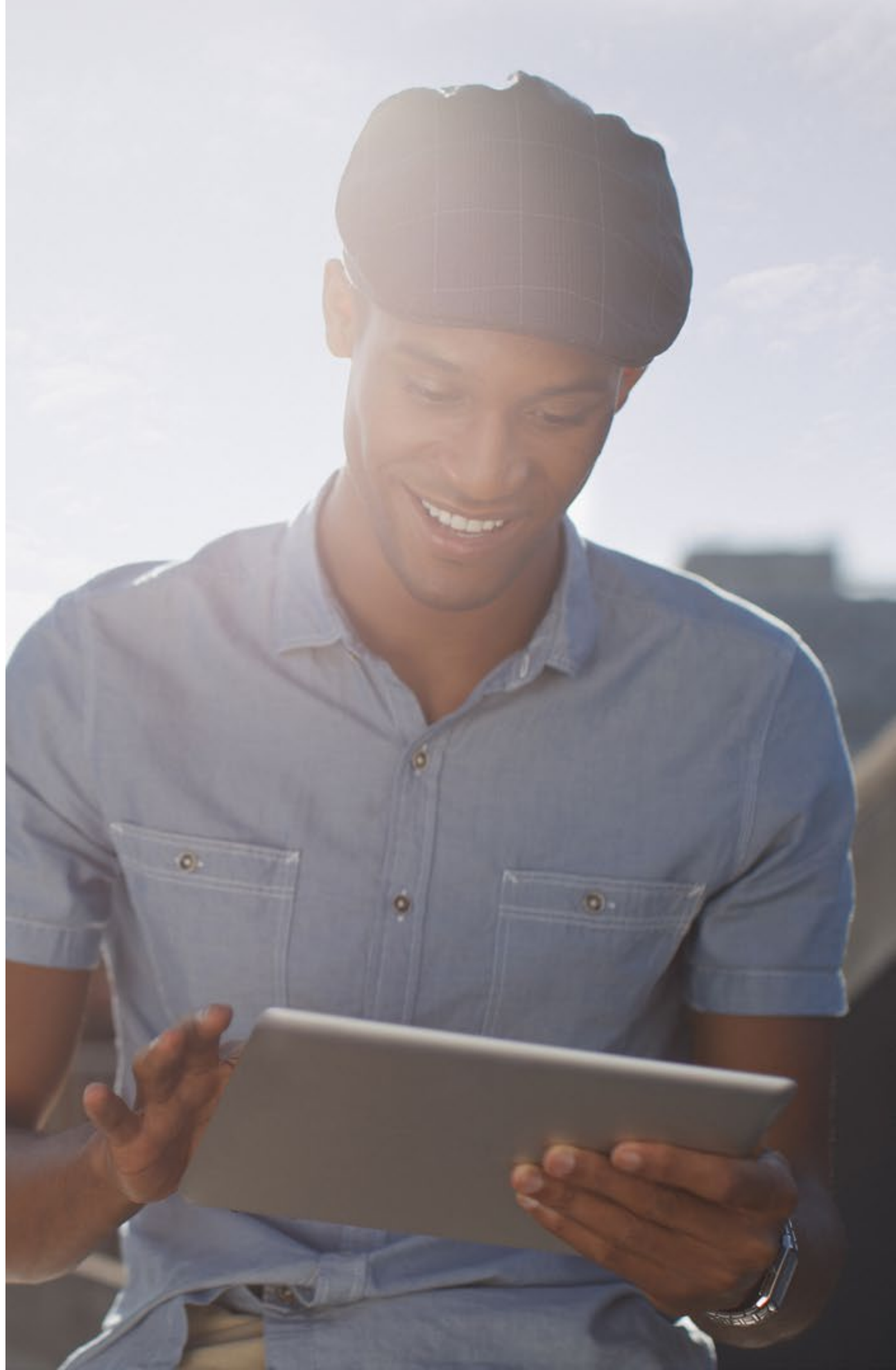

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The Large Hadron Collider beauty experiment has seen hints of new particles that may point the way toward a higher theory of physics

* * *

Measuring *Beauty*

By Guy Wilkinson

Photographs by Alastair Philip Wiper

Guy Wilkinson is a particle physicist at the University of Oxford and a former spokesperson for the Large Hadron Collider beauty experiment at CERN.

VIEW INTO THE CAVERN housing the LHCb experiment, where protons collide to produce particles containing beauty quarks.

It is unusual for TV news to open with a story about physics, but it happened on July 4, 2012, when all around the world stations chose to devote prime time to breaking news from Geneva: a search of almost 50 years had ended with the discovery of the Higgs boson particle by the Large Hadron Collider (LHC) at the CERN physics laboratory. For experimentalists, the Higgs was the last and most important missing piece in the trophy cabinet of the Standard Model of particle physics—the theory describing all the known particles in the universe and the forces between them. Yet physicists believe there may be more elementary particles than those in the Standard Model, and a new and even more challenging hunt is on to find them.

Like the quest for the Higgs, the race to discover hidden particles, thereby building a fuller picture of nature at its tiniest scales, is taking place at the LHC. The experiments that discovered the Higgs—ATLAS and CMS—will play an important role, but LHCb, a smaller and less well-known project operating at the same accelerator, brings guile and stealth to the chase. There is a real chance that this third experiment may be the first to bring home the prize.

LHCb follows a different game plan than most pursuits of new particles. Whereas ATLAS, CMS and many other efforts try to create undiscovered particles directly, the LHCb experiment on which I work uses so-called beauty hadrons to look for the signatures of unseen particles that we cannot directly produce but that affect reactions behind the scenes. LHCb (the "b" stands for "beauty") studies what happens when beauty hadrons are created in the Large Hadron Collider and then decay into other particles. Beauty hadrons make excellent test subjects because they decay in a huge variety of ways, and physicists have very precise predictions about how these reactions should proceed. Any deviation from those predictions is a clue that we might be seeing interference from unknown particles.

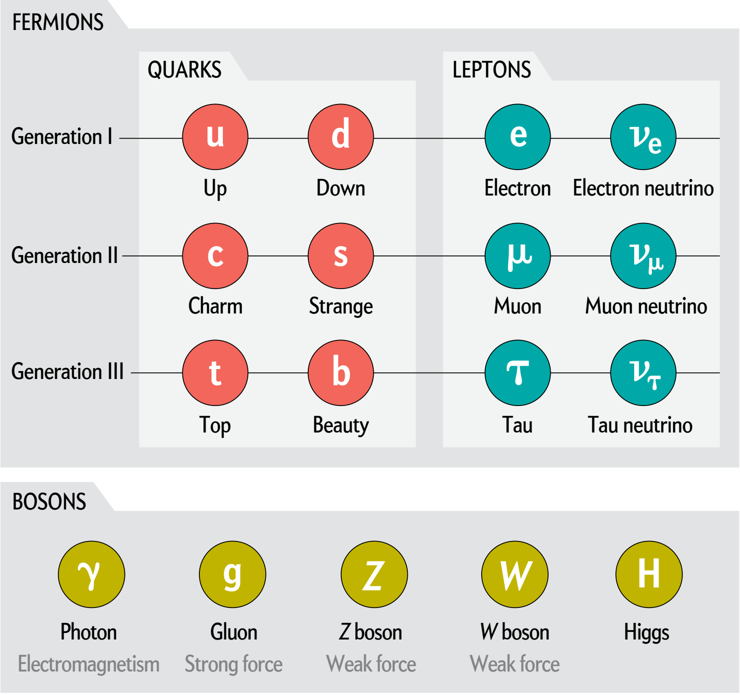
This type of search is complex and requires great precision, but it has the potential to uncover particle species that are impossible for ATLAS and CMS to access. Already it has turned up several intriguing hints of phenomena that threaten to defy the laws of physics as they are currently written. We may be witnessing the actions of particles or forces in nature that physicists have never before observed and possibly never even imagined. If so, our investigations at LHCb could reveal the workings of the cosmos on a more fundamental level than humans have ever glimpsed before.

AN INCOMPLETE THEORY

THE STANDARD MODEL has been highly successful at describing the behavior of the elementary particles of nature and the forces that act on these particles. It divides the elementary particles into quarks and leptons. There are six quarks arranged in three groups, called generations: up and down, charm and strange, and beauty (also called bottom) and top. We never see these quarks in isolation;

The Standard Model

The known particles and forces in the universe make up the Standard Model of particle physics. It includes six kinds of quarks and six types of leptons, as well as five bosons, which transfer the forces of nature. But physicists believe there are more particles out there than those in the Standard Model, and they aim to find them through projects such as the Large Hadron Collider beauty experiment.



IN BRIEF

- **The LHCb** experiment at CERN's Large Hadron Collider is searching for undiscovered particles that may illuminate new truths about how nature operates at its tiniest scales.
- **Instead of aiming** to produce these new particles directly, LHCb scientists are hoping to detect the influence of "virtual" particles that pop briefly in and out of existence and influence conventional matter.
- **Already the** experiment has shown hints of odd particle behavior that cannot easily be explained by current laws of physics. More research will determine if these are the first glimpses of new lands on the particle map.

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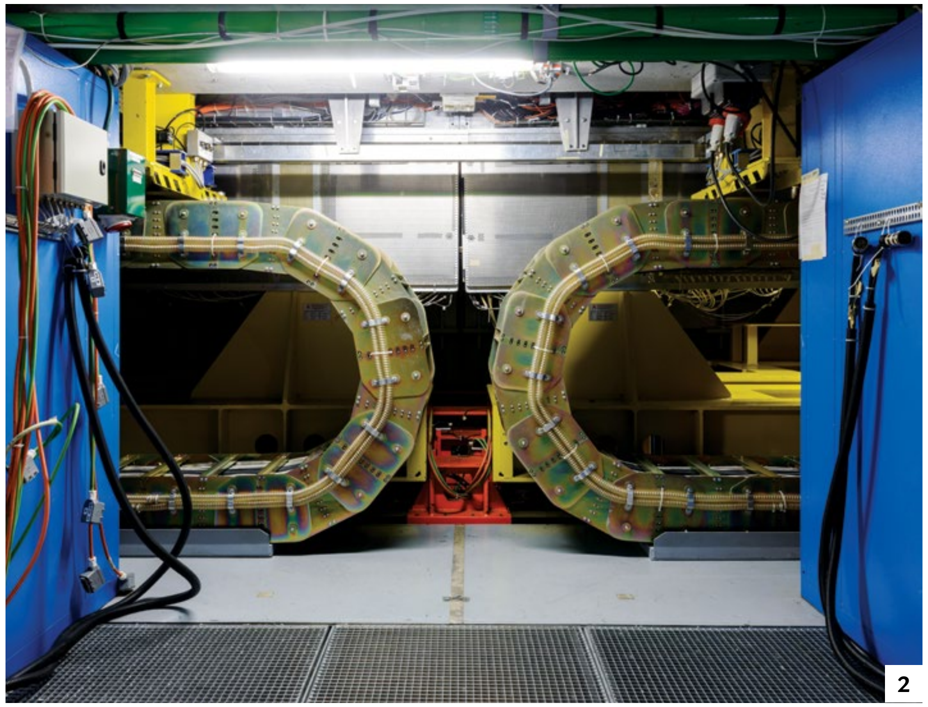

2

LHCb, seen from the side (1) and underneath (2).

rather they cluster together in so-called hadrons—beauty hadrons, therefore, are particles containing beauty quarks. Likewise, there are three families of leptons: the electron and electron neutrino, the muon and muon neutrino, and the tau and tau neutrino. The up and down quark and the electron—all from the first generation—make up the atoms of everyday matter. The particles belonging to the other two generations tend to be more elusive; we must use particle accelerators to coax them into existence. The forces that act on these particles—excluding gravity, which is unimportant at the subatomic level—are electromagnetism, the weak force and the strong force. Each force is transferred by an additional particle: for example, the photon carries electromagnetism, and the W and Z bosons deliver the weak force. Alongside all of these, the Higgs boson sits alone, the manifestation of an underlying field that gives some particles mass.

And yet physicists know that the Standard Model must be wrong. "Wrong," though, is an extreme word; rather we prefer to say that the theory is incomplete. It succeeds very well in answering certain questions but has nothing to say about others. At the cosmic level, it cannot explain why the universe is overwhelmingly constituted of matter, whereas in the big bang, matter and antimatter must have been created in equal proportion. Nor can it tell us anything about the nature of dark matter, the extra mass in the universe that we cannot see but that we know must be there to drive the observed motion of the stars and galaxies. Indeed, the Standard Model does not include gravity, the dominant force on large scales, and all attempts to include it so far have failed.

THE BEAUTY EXPERIMENT

THE LARGE HADRON COLLIDER, home to LHCb, is a 27-kilometer-long, ring-shaped accelerator in which two beams of high-energy protons circulate in opposite directions at close to the speed of light. Inside LHCb these beams collide up to 40 million times per second. The dense points of energy that are formed when the protons smash together and annihilate one another can condense into particles that are very different than the protons that collided—for example, particles containing beauty quarks. Even if they are very short-lived, these new particles spring into existence and then decay into products that LHCb can detect.

The LHCb experimental site sits approximately four kilometers from the main CERN lab, nestled against the perimeter fence of the Geneva Airport. The surface buildings are functional in design and mostly inherited from a previous experiment. A large, circular window, a sole concession to aesthetics, allows passengers looking out from planes on the nearby runway to easily spot the main hall. Inside one of these buildings, in a well-appointed control room, physicists sit day and night monitoring the status of the experiment, which is situated in a cavern 100 meters below.

Although modest in size compared with its bigger siblings around the LHC ring, the LHCb detector is still an imposing and impressive sight spanning around 20 meters in length and 10 meters in height. Its elongated design gives LHCb a very different appearance to the cylindrical geometries of ATLAS and CMS and allows it to record the signals of particles produced close to one wall of the cavern. This stretched geometry helps in the study of beauty hadrons, which are particles containing beauty quarks. Because of their relatively modest mass (around 5 GeV, or giga electron volts, which is only a little heavier than a helium nucleus), when beauty hadrons form at the LHC there is always plenty of surplus energy left over. This extra energy tends to throw the newly created beauty quarks forward from the collision point into the detector. Despite its unusual layout, LHCb has many of the same components as other experiments. These include a large magnet, tracking stations to reconstruct

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the trajectories of particles produced in the collisions and calorimeters to measure the particles' energies.

But several attributes are unique to LHCb and are designed specifically for beauty physics. For instance, a silicon-strip detector placed just eight millimeters from the LHC particle beams can reconstruct the position of a particle decay with great precision—a useful tool because beauty hadrons typically fly forward just a centimeter or so before decaying into a collection of lighter particles. LHCb also has a system of so-called RICH (ring-imaging Cherenkov) counters, which can determine the identities of the beauty hadron decay products based on the patterns of light many of them emit.

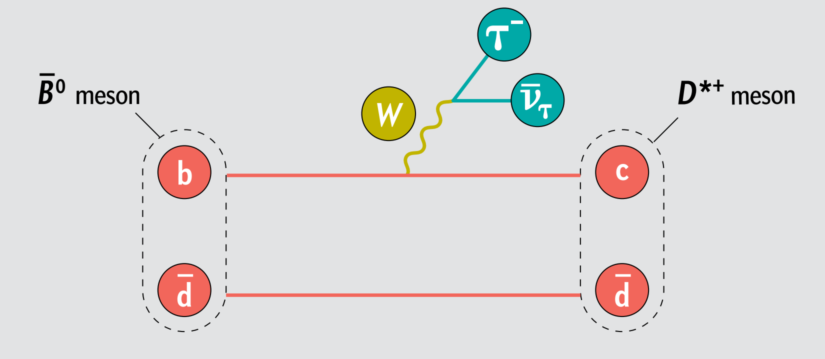
THE SEARCH FOR NEW PHYSICS

DURING THE LHC'S FIRST RUN, from 2010 to 2012, the accelerator produced almost a trillion beauty hadrons inside our experiment. These particles can decay in a huge number of ways, some of which are more interesting than others. We are looking for decays that may serve as signposts to "new physics"—behavior that the Standard Model cannot explain.

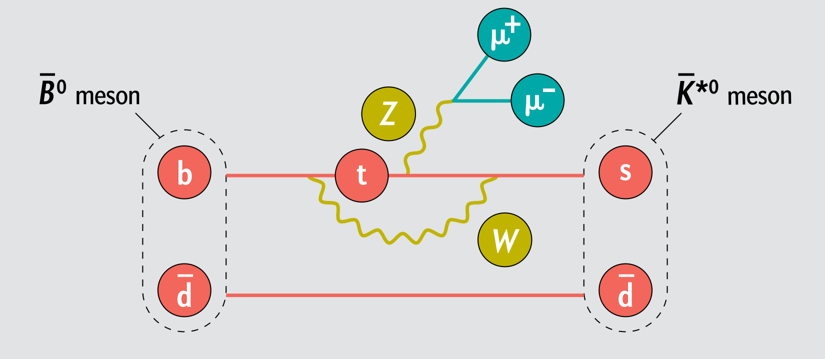
Theoretical physicists have many hypotheses for what this theory could be, but most ideas involve new particles that are somewhat heavier than those we know of. This heaviness is one excellent reason the LHC is so well equipped to seek new physics: the high energy of its collisions means that it can produce and detect rather massive particles, up to a few thousand GeV in equivalent mass (by way of comparison, the Higgs boson weighs around 125 GeV and the humble proton 0.9 GeV). The ATLAS and CMS experiments have been designed to search directly for such massive particles through the distinctive signatures their decays would create. Yet there is another, more cunning way to look for new physics. We can detect the presence of new particles through their "virtual" effects on the decay of Standard Model particles.

To understand the idea of virtual particles, we must turn to Feynman diagrams [see boxes below]. The renowned 20th-century American theoretician Richard Feynman invented these diagrams as a way to visualize and calculate the decays and interactions of subatomic particles. Here we will examine the Feynman diagrams of two possible decay paths of beauty hadrons (particles that unfortunately tend to be called by rather ungainly conglomerations of Greek letters and symbols).

DECAY SCENARIO 1: $\bar{B}^0 \to D^{*+}\,\tau^-\,\bar{\nu}_\tau$



DECAY SCENARIO 2: $\bar{B}^0 \to \bar{K}^{*0}\,\mu^+\,\mu^-$



In both examples, we start with a so-called $\bar{B}^0$ (pronounced "b zero bar") meson, a hadron composed of a beauty quark and an anti-down quark (antimatter particles are denoted with the suffix "bar"). In the diagrams, time runs from left to right. In the first case, we can see that our starting meson decays into a D^{*+} meson (made of a charm and an anti-down quark), a negatively charged tau lepton (τ^-) and an anti-tau neutrino ($\bar{\nu}_\tau$); hence, the process is designated $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$. The other decay, $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$, produces a $\bar{K}^{*0}$ meson (built of a strange quark and an anti-down quark), a muon and an anti-muon. The law of conservation of energy, as well as the equivalence of mass and energy as described in Albert Einstein's famous equation $E = mc^2$, requires that these final particles have a total mass that is less than that of the initial beauty meson. The difference in mass turns into the kinetic energy of the decay products.

Let us focus on what is happening at the heart of the diagrams, where the decay occurs. In the first case, we see a *W* boson, one of the particles that carries the weak force, appearing at the point where the beauty quark transforms into a charm quark. This *W* boson then decays into a tau and anti-tau neutrino. What is striking is that the *W* is around 16 times more massive than the initial $\bar{B}^0$ meson. Why does its appearance in the decay process not violate the rule of energy conservation? According to the mysterious accounting of quantum mechanics, such violation is actually allowed as long as it happens over a sufficiently short timescale! In this case, we say that the *W* boson is *virtual*. Now turning to the $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay, we see that the decay process is more complicated, involving a loop structure and three internal points of decay. But here, in addition to a *W*, several other virtual particles also participate: a virtual top quark (t) and a virtual *Z* boson, both much more massive than the initial meson. Virtual particles may sound fanciful, but the rules of quantum mechanics allow us to draw such diagrams, and these diagrams have proved correct time and time again at predicting the probability that these decays will occur. Indeed, it was by such methods that physicists first predicted the existence of the charm quark and the top quark and made the first estimates of their mass.

The diagrams we have discussed represent only two

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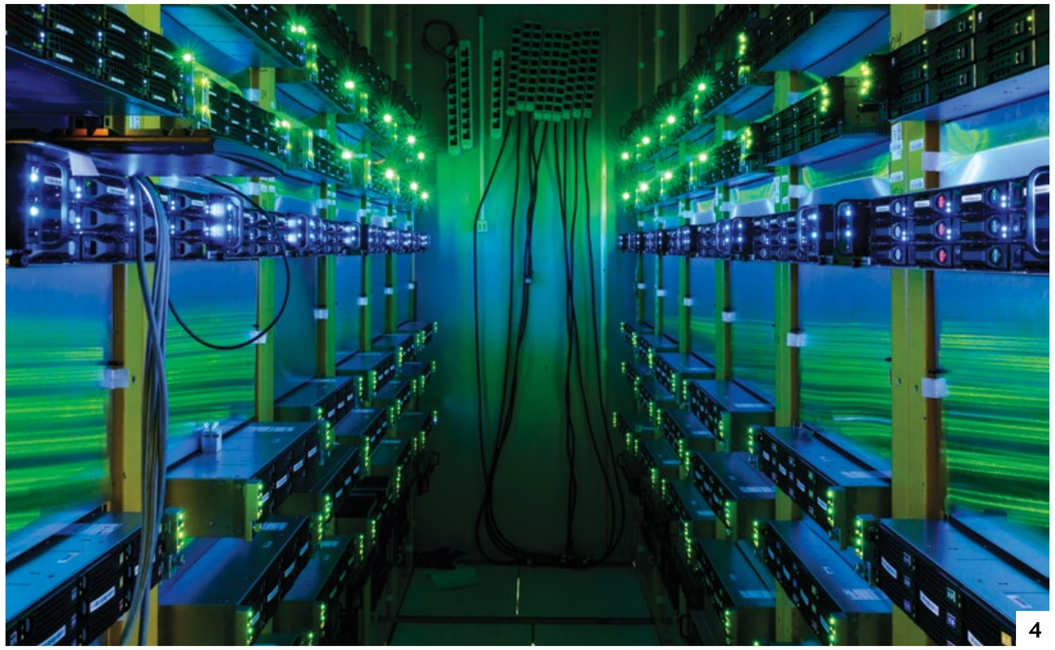

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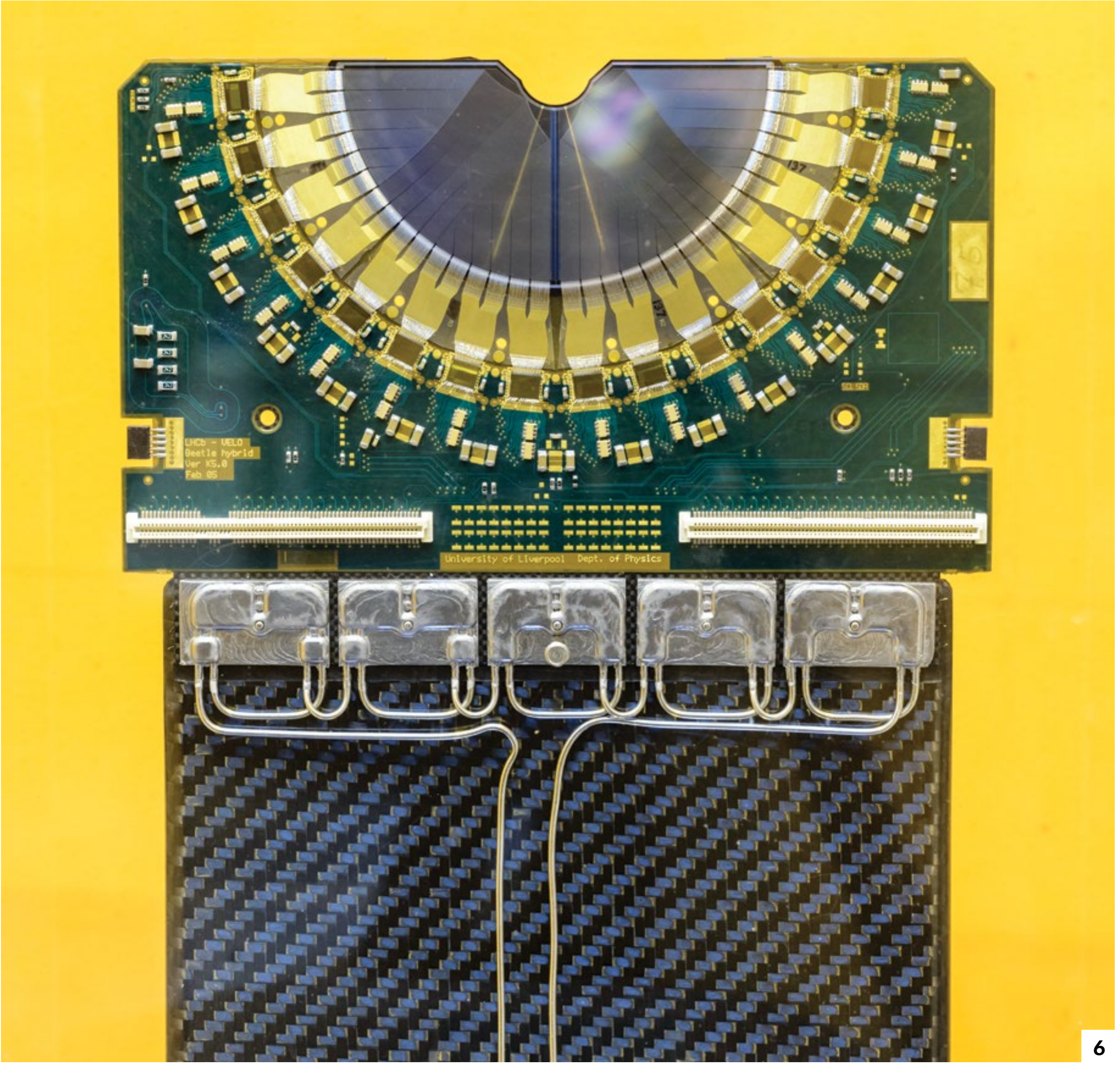

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Studies collisions of protons that travel through a beam pipe (3) into the experiment. Inside the control room (4), physicists monitor operations. Computer processors (5) determine which reactions to record for analysis. The collisions occur inside the delicate Vertex Locator (VELO), which uses silicon sensors (6) to detect beauty particles.

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possibilities for how those particular decays can proceed. We can imagine others, some with particles we have never seen tracing the path between the internal decay points or even finding different ways to link the initial and final state particles. And what is amazing is that all these possibilities matter. The rules of quantum mechanics tell us that what happens in nature is driven by the net contribution of all the valid diagrams we can draw, although the simplest and most obvious have the greatest weight. Hence, all these possible decay paths should play a role, and we must account for them in the calculations we make predicting the rate of the decay, the trajectories of the products and other particulars. In other words, even when a particle decays in a normal process involving only conventional members of the Standard Model, it feels the effects of every possible particle out there. Therefore, if a measurement of a decay disagrees with our calculations based only on the Standard Model ingredients, we know that something else must be at work.

This fact is the guiding principle behind LHCb's strategy of indirect searches for new particles and new physics. Because these new particles would be virtual participants in every decay that we measure, the mass of the particles we can detect is not limited by the energy capacity of our accelerator. In principle, if we studied the right decay processes with enough precision, we could observe the effects of particles even heavier than those that can be created and detected within ATLAS and CMS.

CRACKS IN THE STANDARD MODEL

MY COLLEAGUES at LHCb and I have already seen hints that all might not be well with the Standard Model description of beauty hadron decays. The clues come from a variety of measurements, but they all share some common signatures. It is important to emphasize that with more data and a better understanding of the theory, we might find that the Standard Model does in fact agree with our findings. Even if this turns out to be the case, though, these early hints illustrate how cracks in the Standard Model edifice may develop and widen.

Exhibit A concerns the $\overline{B}^0 \to D^{*+}\tau^-\overline{\upsilon}_\tau$ decay that we discussed earlier and the possible violation of a rule called lepton universality. In the Standard Model, the W boson has the same probability of decaying into a tau lepton and its antineutrino as it has of decaying into the members of the muon and electron families (after we account for the different masses of the tau, muon and electron). In other words, the rules of W decay should be universal for all leptons. But at LHCb, after we counted the decays in each category, subtracted any processes that might fake the signals of these decays and corrected for the fact that not all decays are observed, we found that beauty hadrons appear to be decaying into taus rather more often than the Standard Model says they should.

Our results are not yet conclusive; the discrepancy we found has a strength of "two sigma," where "sigma" denotes uncertainty. Because of statistical fluctuations, one-sigma effects are not infrequent in experimental science, and physicists really only sit up and take notice when three-sigma deviations occur. Five sigma is the commonly adopted benchmark for announcing the discovery of a new particle or declaring that a prediction is wrong. Hence our two-sigma effect is not so remarkable—unless you consider what physicists are finding at other experiments.

Researchers have also looked for violations of lepton universality at BaBar and Belle, two beauty physics experiments in California and Japan, respectively, that collected data in the first decade of the millennium. The results from these experiments consistently favor taus in the same decays we measured as well as similar processes. Furthermore, at LHCb we made a new measurement of lepton universality in these decays earlier this year using a different technique, and once again we found that taus come in slightly above expectations. Altogether this ensemble of measurements gives a result that is separated by four sigma from conventional predictions. This is one of the most striking discrepancies in all of particle physics and constitutes a real problem for the Standard Model.

What could be going on? Theorists have some ideas. A new type of charged Higgs particle, for example, could be involved. Higgs bosons do not respect lepton universality, and they decay preferentially into particles of higher mass, hence favoring the production of tau particles. Yet the exact size and pattern of the discrepancies we see do not fit neatly into the simplest theories that predict such additional Higgs species. Another, even more exotic explanation would be a leptoquark, a hypothetical particle that can allow quarks and leptons to interact. Finally, of course, the results we are seeing could be an experimental effect caused by a misunderstood signal masquerading as the decays we are looking for. To sort through these possibilities, we need new, more precise measurements. We expect several in the coming years, from LHCb as well as from a new-generation Belle II experiment that will soon begin operation.

Our next example showing hints of new physics comes from the decay $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$, which we discussed earlier. Decay processes of this kind are an excellent place to search for signs of new physics for two reasons. First, the "loopy" structure at the heart of the Feynman diagram immediately tells us that elaborate gymnastics are necessary for the decay to occur in the Standard Model; however, new physics particles might have an easier time bringing the process about, and hence their presence may be more evident. Second, this decay has many properties that we can measure: we can note the rate at which the process occurs, as well as the angles and energies of the decay products and other types of information. We can then build these properties into various "observables"—quantities that we can compare directly with Standard

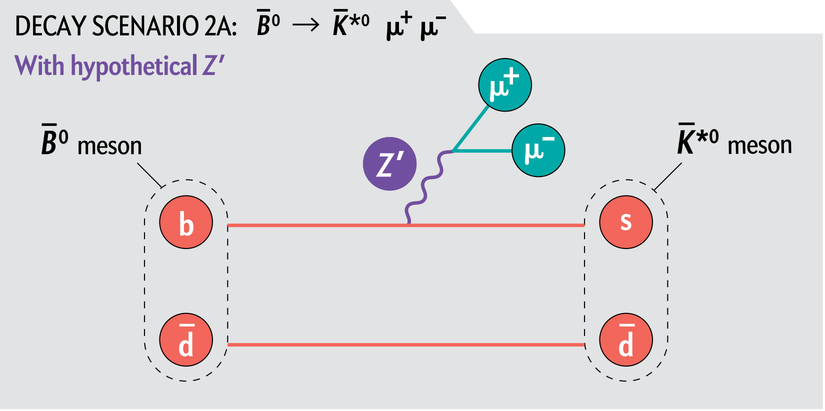
Model predictions (but that, unfortunately, do not always equate to properties that are easy to picture).

In many ways, $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ is the poster child of beauty physics, with its virtues evident by the huge body of theory papers that were written about it well before the LHC even turned on. The only thing that this decay lacks is a decent nomenclature, as the names used to label the different observables are rather underwhelming, such as "P_5'" (pronounced "p5 prime"), which is nonetheless the hero of our story.

We made a first analysis of P_5' with some of the early LHCb data, measuring this observable for different categories of the decay characterized by the directions and energies of the pair of muons produced in the end. For certain configurations we found a significant discrepancy between predictions and our observations. Based on these first results, the physics community eagerly awaited the updated analysis we unveiled a couple of years later using the complete run-one data set. Would the discrepancy persist, or would it prove to be a statistical fluke? It remained. The size of the effect is now around 3.5 sigma, which is not large enough to justify ordering champagne but certainly sufficient to be taken seriously. And we find further encouragement from the fact that measurements of other observables in similar decay processes also exhibit intriguing discrepancies. Altogether the total disagreement with the Standard Model rises to as much as 4.5 sigma—a problem for the theory that we cannot ignore.

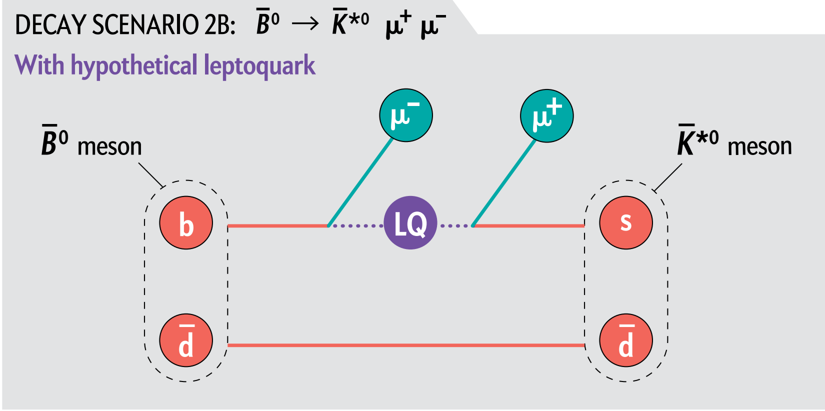
Theorists have come up with a whole swathe of potential new physics explanations for this effect. The leptoquark, already invoked in the $\overline{B}^0 \to D^{*+}\tau^-\overline{\upsilon}_\tau$ decay, is a possibility. Another is a Z' ("z prime") particle, which would be an exotic, heavier cousin of the well-known Z boson but one that decays into quarks and leptons in its own distinctive manner. Such speculation, however, must always respect the constraints that already exist from other measurements. For example, the mass and behavior of these hypothetical new particles must be such that it makes sense that they have not yet shown up in direct searches at ATLAS and CMS.

Theorists are nothing if not ingenious, and there are plenty of plausible scenarios that satisfy these criteria. But we must be cautious. Some physicists worry that the Standard Model predictions for these observables are not fully under control, meaning that the real discrepancy between measurement and theory may be much smaller than imagined. In particular, the repercussions of difficult-to-calculate but mundane effects associated with the strong force may be larger than first thought. The good news is that there are ways to test these ideas through additional measurements. These tests require detailed analysis and more data, but these data are arriving all the time.



DECAY SCENARIO 2A: $\overline{B}^0 \to \overline{K}^{*0}\ \mu^+\ \mu^-$

With hypothetical Z'



DECAY SCENARIO 2B: $\overline{B}^0 \to \overline{K}^{*0}\ \mu^+\ \mu^-$

With hypothetical leptoquark

The final puzzle LHCb has turned up involves a twin set of measurements that has something in common with both our previous examples but that may turn out to be the most interesting of the three. Here we investigated a ratio, dubbed R_{K^*} ("r k star"), that compares the rate of the process that we studied for P_5', where beauty hadrons decay into a $\overline{K}^{*0}$ meson and a muon-antimuon pair, to the rate of a similar decay that produces an electron and antielectron in place of the muon pair. We also examined a second ratio, R_K, comparing decays where the $\overline{K}^{*0}$ meson has been replaced with another kind of strange hadron called simply a K meson. Again, we are trying to test lepton universality, but in this case, between the first two generations of leptons—the electrons and muons.

Within the Standard Model the prediction is trivial—the two decays in each ratio should occur at the same rate, giving the two ratios R_K and R_{K^*} expected values of very nearly one. Again we expected that lepton universality would hold. And the measurements, though far from straightforward, have fewer experimental challenges than in the previously discussed lepton universality analyses and therefore constitute an extremely clean and crisp test of the Standard Model.

We performed the R_K analysis first and found that it came in low, with a value of 0.75, with a precision that put it 2.6 sigma away from predictions. This deviation was sufficiently intriguing that we were all very eager to know the value for R_{K^*}, which we finally published earlier this year. The wait was well worthwhile because, for the same conditions where we examined R_K, R_{K^*} showed remarkably similar behavior. We measured a ratio of 0.69, lying 2.5 sigma below the Standard Model prediction. Although it is quite possible that these undershoots are statistical fluctuations, the fact that we found them in two different measurements, as well as the pristine nature of the tests, means that this anomaly is getting a great deal of attention.

If the R_K and R_{K^*} measurements are a true representation of reality, they indicate that something in nature favors decays that produce electrons over those that create muons, with leptoquarks or a Z' boson again being likely culprits. It seems as if muons, in fact, are being underproduced, whereas electrons are sticking more closely to the Standard Model script. If so, whatever mechanism is responsible would not only explain the R_K and R_{K^*} oddities but would also neatly account for the muon-based P_5'' measurement. For good measure, some more ambitious theorists have even proposed solutions that would also make sense of the $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ puzzle, but conceiving of a particle with the necessary characteristics to explain all three measurements looks to be a tall order.

What is clear is that we will know more very soon. We are analyzing new data from the LHC's second run now, and our knowledge of the values of R_K and R_{K^*} will rapidly improve. Either the significance of the discrepancies will grow, and then these anomalies will become the biggest story in physics, or they will diminish, and the caravan will move on.

GALILEO'S MOTTO

THE RESULTS WE HAVE discussed are only the most prominent examples of a host of interesting measurements that have recently emerged in beauty physics. They rightly excite many in the particle physics community, but the older and wiser scientists among us have seen such effects come and go in previous experiments, so we are content to wait and see.

What would it mean if one or more of these anomalies move from the category of "intriguing hint" to "clear contradiction of the Standard Model"? For sure, it would be the most important development in particle physics for many decades, giving us a window onto the landscape that lies beyond our current understanding of the laws that govern the universe. At that point we would need to discover exactly what is responsible for this breakdown in the Standard Model. Depending on the nature of the new physics particle—whether it be an exotic Higgs, a leptoquark, a Z' or something else entirely—its effects should appear in other beauty hadron decays, giving us more clues. Moreover, unless it is very heavy, this new particle could also appear directly in collisions at the LHC's ATLAS or CMS or at some future accelerator of even higher energy.

Regardless of how the future unfolds, LHCb's exquisite sensitivity and the excellent prospects for significant improvement in the coming years are undeniable. We do not know if the road to new physics through indirect searches will be short or long, but most of us feel sure that we are heading in the right direction. After all, it was Galileo who is said to have instructed us to "measure what is measurable, and make measurable what is not so." We could have no finer motto for LHCb.

MORE TO EXPLORE

- A Challenge to Lepton Universality in B-meson Decays. Gregory Ciezarek et al. in *Nature,* Vol. 546, pages 227–233; June 8, 2017.
- Flavour-Changing Neutral Currents Making and Breaking the Standard Model. F. Archilli et al. in *Nature,* Vol. 546, pages 221–226; June 8, 2017.
- Large Hadron Collider beauty experiment (LHCb): http://lhcb-public.web.cern.ch/lhcb-public

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Dr. Caleb A. Scharf is Director of Astrobiology at Columbia University,and has an international reputation as a research astrophysicist, and asa lecturer to college and public audiences. Scharf is author and co-author of morethan 100 scientific research articles in astronomy and astrophysics.

LIFE, UNBOUNDED

The Tyranny of Extraterrestrial Messaging

Talking to the rest of the universe takes a whole lot of patience

SOME OF THE BASIC ASSUMPTIONS we make about extraterrestrial communication can be woefully naïve. Consider the situation in its gory detail. You decide (perhaps as a species, or perhaps as some resource-rich subset) that you want to ping the cosmos to find out if something else is listening, thinking, and as technological as you are. So you fire up your radio transmitter, or your big laser and start shooting off “Hello” messages.

The future ALMA array on Chajnantor (artist’s rendering)

ALMA: ESO, NAOJ, NRAO, L. CALÇADA ESO

If our circumstances represent a useful template it means that the earliest possible response might come within about 8 years (Earth years of course). That's assuming that there is a responder in the nearest exoplanetary system, listening and receiving your first message at the right time, ready to fire back a response right away, willing to fire back a response, and capable of firing back something recognizable as a response. So, you start listening carefully 8 years later. But nothing comes in. So, you keep listening, telling yourself that it may take time for anyone to put a response together. And you keep listening.

Meanwhile, you’ve been busy. In the last 8 years you’ve been pinging the next furthest stellar systems. But for these the roundtrip light travel times go up to 10 years, 20 years, 40 years. Within the sphere of space for a 40-year messaging roundtrip are roughly 150 stars.

Time goes by, you decide that star number one was a dud. But you have to wait longer and longer to find out what happens with the next star and the star after that. And if nothing comes in from the earliest possible responders your assessment of the odds of any randomly chosen star yielding a result has to be revised downwards. As it declines, so too does your resolve.

If you do stick it out, waiting for 40 years (and possibly more, to allow for an unknown delay period as extraterrestrial species get their act together to respond), but still hear nothing, what do you do next? Your options are to carry on pinging the same stars, or push on to more distant ones, or to stop. It's certainly true that the farther your reach the more stars you access – as the volume of space grows with distance cubed. But at the point where the experiment's timeline exceeds any individual's lifespan, you're going to need an extraordinary amount of patience and determination.

That, I think, is hugely problematic. Not just for us, but for any hypothetical species wanting to discover if there are cosmic neighbors by actively calling out. Unless you are very lucky, or the number of worlds with fully spun-up technological species is immense, you will face a profound barrier of time and willpower. The absence of anyone to talk to among the 150 systems of a 20-light year radius bubble could be true even with a billion talkative species in our galaxy (assuming 200 billion stars in the Milky Way). It would just be a bit of poor luck that there wasn't one of those billion among the nearest 150 stars – nothing terribly out of the ordinary.

This situation is exacerbated if we allow for other factors. Perhaps a tech-capable species just isn't looking and listening at the right moment or in the right direction, perhaps the window of technological evolution where a species is "hot" in terms of communication ability is narrow (for reasons of energy-conservation and efficiency, or perhaps interest). And perhaps they simply don't want to talk back, being happy to just listen in to other chatterboxes.

The conundrum of extraterrestrial messaging (METI) reminds me of the "tyranny" of the rocket equation in space exploration. the faster (and farther) you want to go, the more of your rocket has to be devoted to carrying fuel, adding even more mass to the mass that you want to shoot off into the void. The result is a kind of diminishing return (a diminishing return in natural logarithms).

Pinging the cosmos in the hopes of getting a response seems to have its own tyranny; you want to increase the odds of success, but that means an unavoidable increase in how long you have to wait in the hopes of an answer.

While I don't see an obvious way around this, it does mean one thing. The classic idea of SETI – to listen for signals from elsewhere – does have one overwhelming merit; the signals could be about to reach us from essentially anywhere in the observable universe, with no wait time. Assuming that at least some species out there are very noisy, or have decided they don't care about the tyranny of METI.

Since we ourselves may belong to both camps I think we can keep our fingers cautiously crossed.

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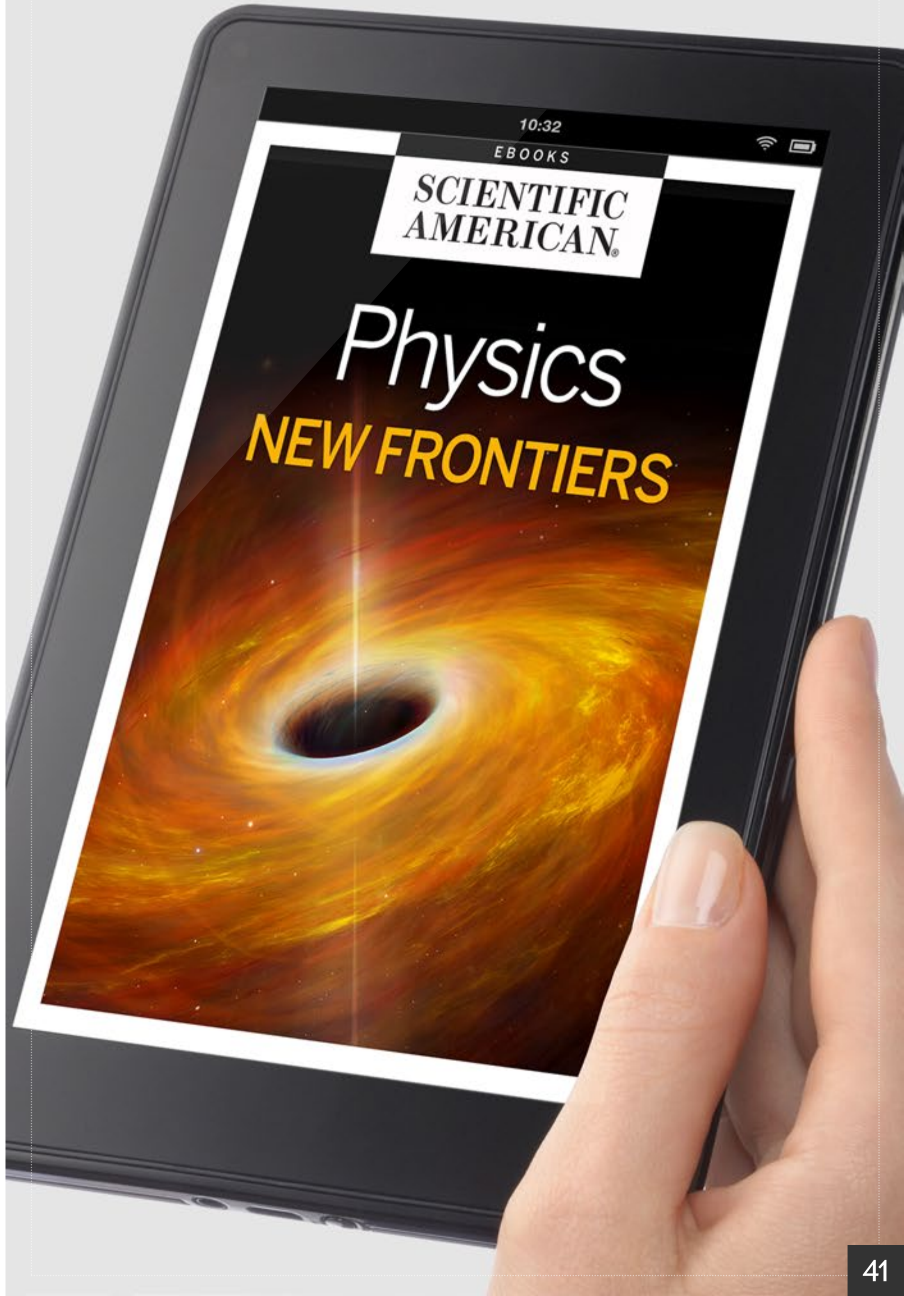


Lucianne Walkowicz holds the Baruch S. Blumberg Chair of Astrobiology at the Library of Congress. Visit her website and follow her on Twitter.

OBSERVATIONS

The Interplanetary Political Football of Space Exploration

The National Space Council has been revived, but whether that's good for astronomy, planetary science and space exploration remains to be seen

FRANK OKAY

The past decade of U.S. astronomy glitters with some truly astonishing accomplishments, amongst them landing a SUV-sized, nuclear-powered science machine on the surface of Mars, and answering the longstanding question of whether other possible Earths lurk in the cosmos (a resounding YES). Even in a tight funding environment, astronomers and planetary scientists have pushed the frontiers of discovery, both NASA- and private industry-led efforts to develop home-grown launch capacities have been pressing ahead, and exciting new missions to explore both our own solar system and deep space are planned for the future.

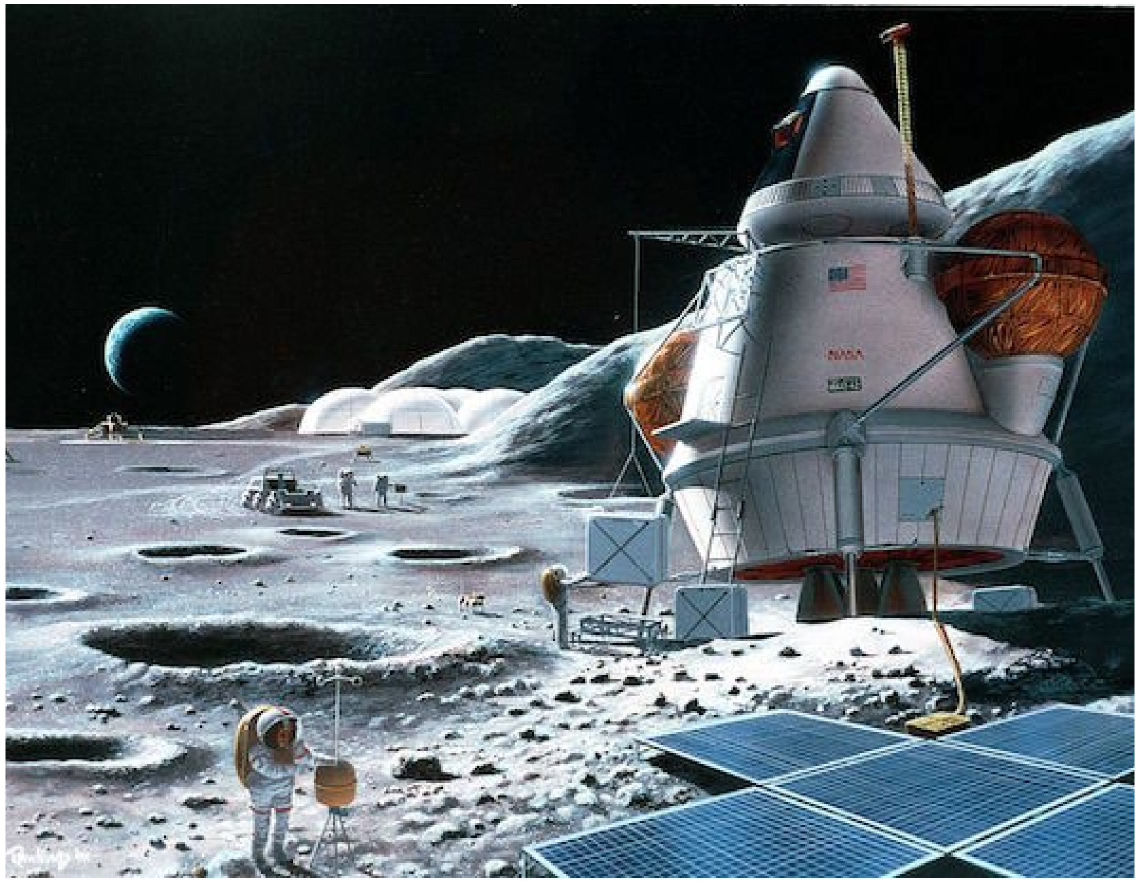
Listening to Vice President Mike Pence's statement at the first meeting of the newly-reanimated National Space Council, however, one might be forgiven for getting the impression that things aren't going well. The Vice President stated that "rather than lead in space, we have often chosen to drift," and stated that our space program suffers from "apathy and neglect." Listening to Pence's address echo across the hanger of space luminaries, the Discovery space shuttle peeking over his shoulder, I couldn't help but find his narrative surreal. After all, some 250 miles over his head, Americans were nonchalantly plunging in orbit around our planet, tethered to the International Space Station as they busily engaged in the work of living in space.

Despite its crisp, futuristic name, the National

Space Council is a recurring relic of the past, like a chain letter that surfaces every few decades or so. Since its inception in the late 50s (originally as the National Aeronautics and Space Council), the NSC has usually served as a kind of vestigial membrane attached to the Office of the President. Originally, it was something like a civilian scientific advisory body, but the lack of actual policy makers in its membership limited its ability to do much beyond render opinions it had no authority to enact, and to which no one was beholden.

Later iterations remedied that flaw by including members from government (as is currently the case, where the council is comprised largely of members of the President's cabinet), but ultimately the NSC has remained an ineffectual bureaucratic film, a flimsy barrier between decision makers, and those who actually carry out our presence in space. Indeed, when the NSC was last given a mandate to create a bold vision for space exploration during the George H. W. Bush administration, it brought forth the Space Exploration Initiative, a plan that clocked in at a cost of around $400 billion, a proposal so preposterously out of step with funding reality that space policy experts have referred to it as "stillborn."

In light of the NSC's checkered history, it's perhaps not surprising that the messaging during its inaugural meeting was so mixed. Pence's first (leading) question to the civilian space industry panel asserted that the U.S. lags behind in space, essentially putting the panel members in the position of contradicting the Vice President if they were to answer directly. The panelists, along with those of the second civilian panel, parried this assertion in turn like synchronized swimmers, with Gwynne Shotwell of SpaceX even countering that "there is a Renaissance underway in space."



NASA, SAIC, PAT RAWLINGS

On the tails of their optimism came the defense panel. Here the message was dark, and fear-driven: we are vulnerable to our enemies, and coordinated efforts to be fearsome are the only way to prevent having to defend ourselves from both state or non-state actors moving against us. Much like the NSC's relationship to policy makers, the historical interface between the military and the NSC is a curious one—defense uses of space are typically the purview of the National Security Council, which carries out its own, independent agenda, unperturbed by the opinions of the National Space Council.

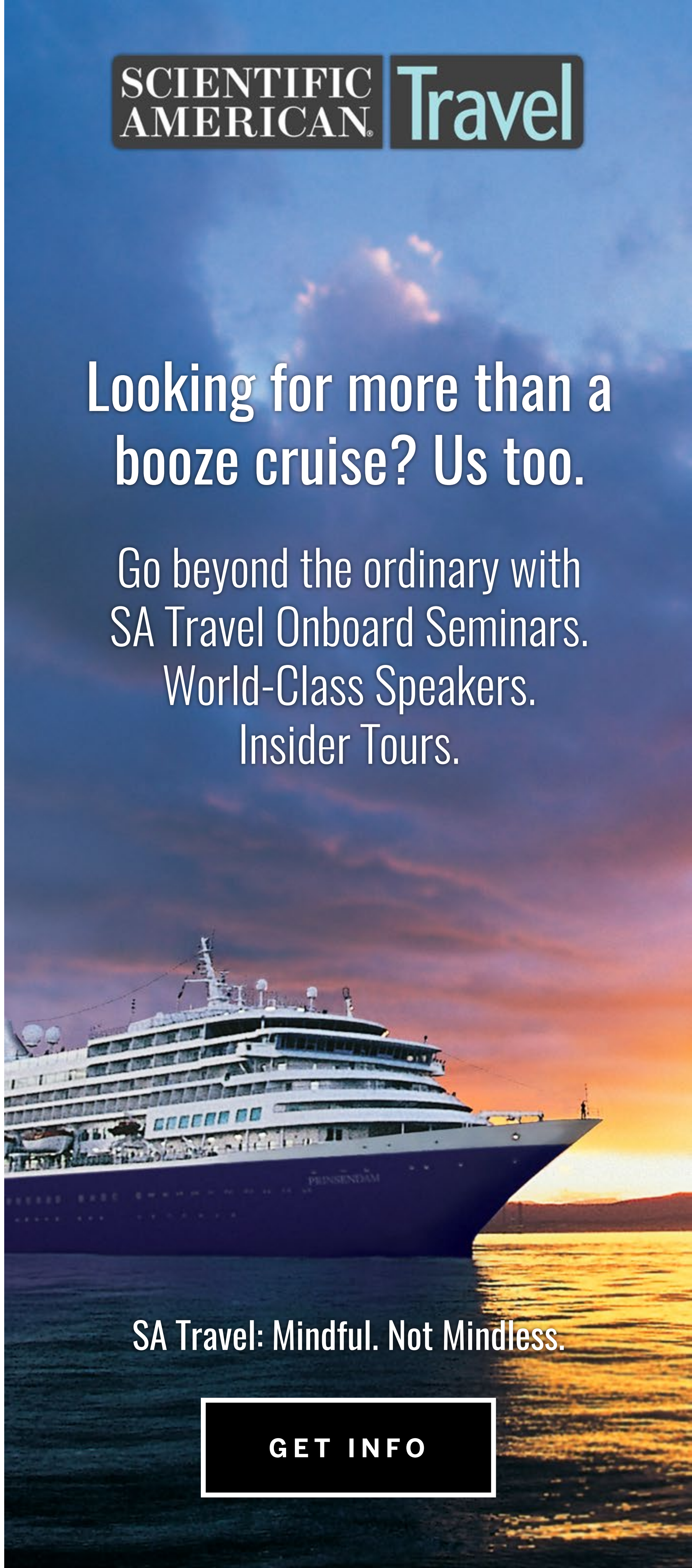
Why breathe life back into the body of a group that never had much to begin with? While some branches of science find themselves under attack in the current administration, space enjoys broad bipartisan support in Congress, with especially strong advocates for some specific projects and missions—e.g. Rep. Richard Shelby (R-Alabama) and the development of NASA's Space Launch System, or Rep. John Culberson (R-Texas) and the Europa Clipper. When the Executive Order that revived the NSC was signed back in June, some analysts posited that the National Space Council could be a beneficial force, if led by a Vice President with a strong history of interest and knowledge of space (which Pence does not have), and appropriately peopled by those in positions to both create and carry out an implementable vision of the United States' presence in space (which the Cabinet is not). At this first meeting, though, it seemed only that the zombie of previous Councils had risen again—it's true that the NSC can be a convener of expertise, as seen in the panels, but to what end? If anything, the main thing accomplished by the revival of the NSC is to shift visioneering efforts for the future of U.S. presence in space towards the Executive Branch, and away from Congress.

Almost exactly a year ago, I sat in a hall at Carnegie Mellon University, packed shoulder-to-shoulder with scientists from a wide variety of STEM fields. We were all there for the White House Frontiers Conference, a kind of last-hurrah festival of science and technology, put on by the Office of Science and Technology Policy (OSTP) in the twilight of the Obama administration. There (and in an op-ed for CNN in the days prior) then-President Obama outlined a vision for humanity's future on Mars. Mars and the Moon have long been the two favorite political footballs of interplanetary exploration, each with their own fervent base of advocates. Fans of the Moon (such as Newt Gingrich, or George W. Bush before him) often argue that a permanent base on the Moon is an essential stepping stone in our eventual journey to Mars, although no one has yet connected the dots as to how that specifically might happen. When folding in funding realities, even propositions advocating both the Moon and Mars have been broadly understood to mean the Moon... and then, maybe later, Mars.

In Vice President Pence's address to the NSC meeting, the emphasis was decidedly on a return to the Moon, prior to sending humans to Mars. For anyone who follows interplanetary politics, that pivot wasn't surprising—Moon advocates like Gingrich (who himself once seemed a willing potential pick for Trump's running mate) have the ear of the current administration. If you didn't see the writing on the wall, those in the private space industry likely did—Elon Musk, CEO of SpaceX, began talking publicly about going to the Moon before Mars about two weeks after the signing of the Executive Order that re-established the NSC.

From the broader perspective of the current administration's priorities, the Moon makes a lot of sense: not because the Moon holds great scientific potential, but because of its potential as a strategic outpost for national security, or as a place to obtain material resources (e.g. via mining operations). It's straightforward to see those priorities reflected in the makeup of the two panels: one on national security, two from private industry. It is telling (but not surprising) that the discussion didn't include science except in the broadest of brushstrokes—science is not a priority for this administration (and to be fair, it isn't really a priority for any administration except when tied to American strategic advancement, it's just that some administrations leave basic scientific research more breathing room to proceed unharrassed).

Leaving aside the harsh realities of any country's political motivations to go to space, as a member of the astronomical community, it's hard not to feel like a passenger in the back seat of a car, watching an ongoing struggle over the steering wheel. Having the vision for our space program remain agile and responsive in a changing science and technology landscape is one thing, but it bears remembering that if all we do is pivot, we'll never get anywhere.



Greg Laughlin is a professor of astronomy at Yale University, where he works on the detection and characterization of extrasolar planets. He is co-author of The Five Ages of the Universe--Inside the Physics of Eternity, and he blogs about planets at oklo.org.

OBSERVATIONS

Flyby of Interstellar Asteroid Portends a Quadrillion Trillion More in Galaxy

Reports of the first-ever flyby of a body from another stellar system suggest a vast sea of interstellar shards and a Neptune-like planet around every star in the Milky Way

ESO/M. KORNMESSER

From its vantage on the 10,000-foot summit of Maui's Haleakala, the Pan-STARRS project is tasked to find asteroids that might threaten our planet. Its cameras image a full seventh of the sky every night, sifting the firmament for hints of anything that moves or changes. On October 19, the project's computers detected a fast-moving object on images taken the previous evening. An alert went out, and other telescopes picked up the chase. Within a few days, it was clear that an asteroid-like visitor from interstellar space had infiltrated our solar system, and we were witnessing the first-ever flyby of a body from another stellar system.

A paper published November 20 in *Nature* by Karen Meech (University of Hawaii) and 17 collaborators reviews and adds to the growing collection of observations that have accumulated during the remarkable encounter. The object, now officially named 1I/2017 U1 (and also known by the Hawaiian "'Oumuamua," or messenger from the distant past) is unambiguously extrasolar in origin and exhilaratingly bizarre in nature. Coming from the direction of the solar apex (the point in the sky toward which the solar system is moving as it orbits the galaxy), it streaked toward the sun with an initial speed of 26 kilometers per second, accelerating to 88 kilometers per second at the moment of its September 9 close approach well inside of Mercury's orbit. When finally caught by Pan-STARRS' cameras, it had already swung past the sun and crossed Earth's orbit in the outbound direction. The sun's waning gravitational influence on it is now steering it toward an exit point from our solar system in the direction of the constellation Pegasus.

As reported in the *Nature* article, Meech and her team enlisted a fleet of the world's largest telescopes (including Gemini South, the VLT and Keck) to monitor 'Oumuamua's brightness and its spectrum over the course of several nights during the last week of October. The spectral observations point to a very red color, roughly consistent with the hue of comets and other outer solar system bodies. The inference is that—like comets—'Oumuamua's surface is covered with carbon-rich material and is likely not very good at reflecting light. The light curves are nothing short of startling. They strongly suggest that 'Oumuamua is a crazily elongated shard that rotates every seven hours and 20 minutes. This rate of spin would cause a weakly gravitating rubble pile to fly apart; 'Oumuamua must be a solid monolith, held together like a rock by its physical strength. If one assumes that it reflects that same fraction of the light that hits it as that reflected by Earth's moon, it is quite similar in both size and shape to the largest aircraft supercarriers.

For more than a century, astronomers have speculated about the potential arrival of an interstellar comet in our solar system. It was thus a surprise that 'Oumuamua showed no sign whatsoever of a coma. At its closest point to the sun, it was soaking up 20 kilowatts of energy per square meter, and at the location where the sun was directly overhead, its outermost skin was heating up fast. Yet effectively nothing was geysering up and out, suggesting the arrival of an asteroid rather than a comet.

The mere fact of 'Oumuamua's discovery suggests that a staggeringly large number of similar objects must be drifting through the void. Several factors, including the direction and the distance of the close approach, permitted Pan-STARRS to make the discovery. Most similar-sized interstellar objects that come as close to the sun as 'Oumuamua will elude Pan-STARRS' surveillance. After taking the various observational biases into account, Meech and collaborators calculate that there is always about one 'Oumuamua-like object passing within the sphere defined by Earth's orbit, a value that is in fair agreement with estimates published during the past two weeks by other groups.

Given its trajectory, it's extremely unlikely that 'Oumuamua was recently ejected from the planetary system of a nearby star. Almost certainly, it has been traveling through our Milky Way galaxy for hundreds of millions if not billions of years, and so if we assume that its passage was not a fluke, we can calculate that the galaxy contains a quadrillion trillion such objects (10^{27}), enough to account for two Earth-masses of material for every star in the galaxy.

This vast sea of interstellar shards has some profound implications, as the ejection of debris from a newly forming planetary system is no easy task. Lofting an object like 'Oumuamua free of its parent star requires the gravitational assistance of a planet that both has a substantial mass and is located at a fairly large radial distance. In our solar system, all four giant planets (and especially Jupiter and Neptune) are capable of slinging small bodies into interstellar space. The terrestrial planets, however, fall well short, as do the vast majority of the known extrasolar planets. If 'Oumuamua-like objects abound, and if they are composed of icy outer-system material, then nearly every star in the galaxy must host a Neptune-like planet at a Neptune-like distance.

On the other hand, in the highly unlikely event 'Oumuamua is indeed a refractory slab of rock or metal, as suggested by its complete lack of coma, then its appearance is extremely hard to understand. Only a few percent of stars host planets that are capable of ejecting volatile-free debris from warm regions deep within a gravitational well. They flat-out can't generate the vast overall swarm implied by 'Oumuamua's recent passage, suggesting that another visit by a similar object won't happen for a very long time.

As it departs into the depths of the galaxy, 'Oumuamua can expect to fly for roughly 10 quadrillion years before it visits another star with such proximity. At that far distant time, the galaxy will be a very different place, in which all the stars that now shine warmly down on planets will be expired white dwarfs, warmed a few degrees above absolute zero by the flicker of proton decay.

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His latest book is *Heavens on Earth* (Henry Holt, 2018).

BEHAVIOR & SOCIETY

Belief in Aliens May Be a Religious Impulse

Is belief in aliens a religious impulse?

IZHAR COHEN

In Star Trek V: The Final Frontier, Captain James T. Kirk encounters a deity that lures him to its planet in order to abscond with the Enterprise. “What does God need with a starship?” the skeptical commander inquires. I talked to Kirk himself—William Shatner, that is—about the film when I met him at a recent conference. The original plot device for the movie, which he directed, was for the crew to go “in search of God.” Fearful that some religious adherents might be offended that the Almighty could be discoverable by a spaceship, the studio bosses insisted that the deity be a malicious extraterrestrial impersonating God for personal gain.

How could a starship—or any technology designed to detect natural forces and objects—discover a supernatural God, who by definition would be beyond any such sensors? Any detectable entity would have to be a natural being, no matter how advanced, and as I have argued in this column [see “Shermer's Last Law”; January 2002], “any sufficiently advanced extraterrestrial intelligence [ETI] is indistinguishable from God.” Thus, Shatner's plot theme of looking for God could only turn up an ETI sufficiently advanced to appear God-like.

Perhaps herein lies the impulse to search. In his 1982 book *Plurality of Worlds* (Cambridge University Press), historian of science Steven J. Dick suggested that when Isaac Newton's mechanical universe replaced the medieval spiritual world, it left a lifeless void that was filled with the modern search for ETI. In his 1995 book *Are We Alone?* (Basic Books), physicist Paul Davies wondered:

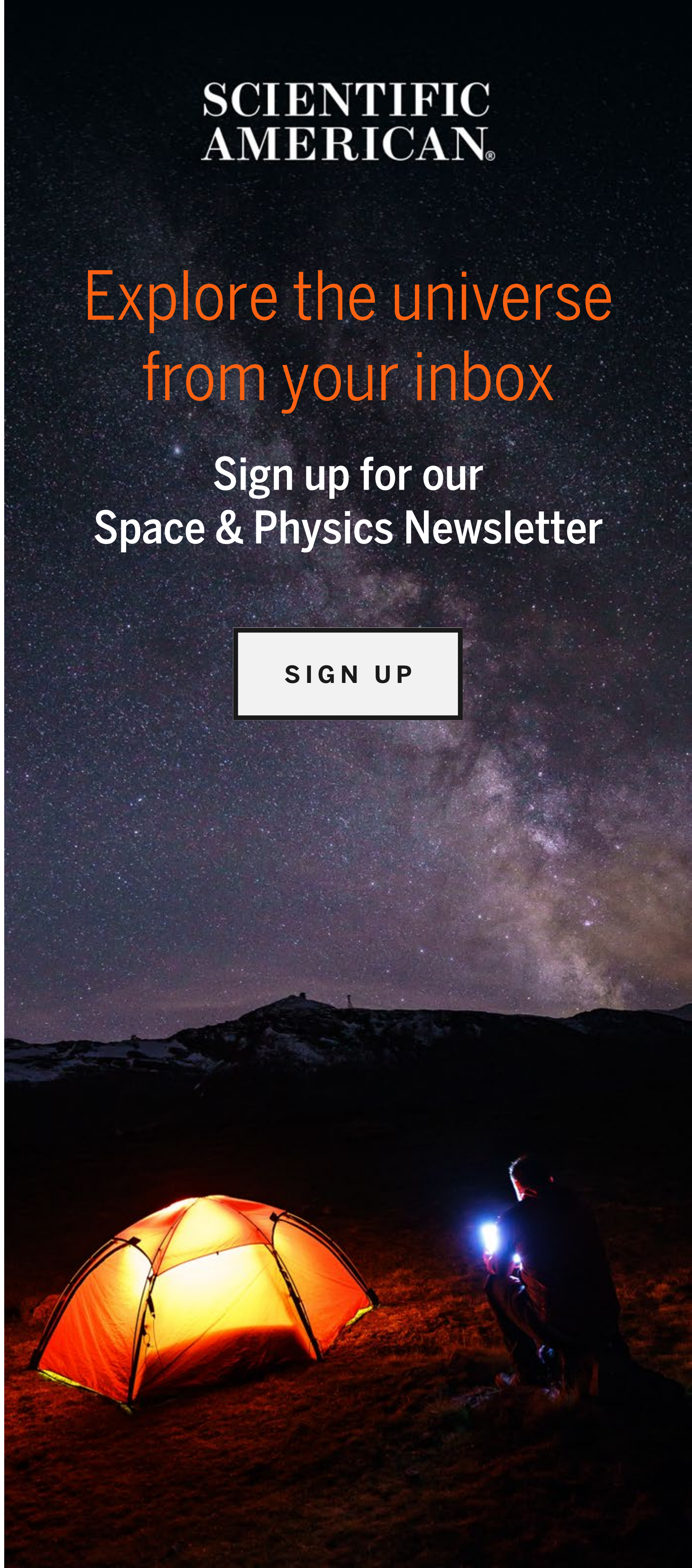
“What I am more concerned with is the extent to which the modern search for aliens is, at rock-bottom, part of an ancient religious quest.” Historian George Basalla made a similar observation in his 2006 work *Civilized Life in the Universe* (Oxford University Press): “The idea of the superiority of celestial beings is neither new nor scientific. It is a widespread and old belief in religious thought.”

Now there is experimental evidence in support of this hypothesis, reported in a 2017 article entitled “We Are Not Alone” in the journal *Motivation and Emotion*, in which North Dakota State University psychologist Clay Routledge and his colleagues found an inverse relation between religiosity and ETI beliefs. That is, those who report low levels of religious belief but high desire for meaning in life show greater belief in ETIs. In the team's first study, subjects who read an essay “arguing that human life is ultimately meaningless and cosmically insignificant” were statistically significantly more likely to believe in ETIs than those who read an essay on the “limitations of computers.”

In the second study, subjects who self-identified as either atheist or agnostic were statistically significantly more likely to report believing in ETIs than those who reported being religious (primarily Christian). In studies 3 and 4, subjects completed a religiosity scale, a meaning in life scale, a well-being scale, an ETI belief scale, and a religious/supernatural belief scale. “Lower presence of meaning and higher search for meaning were associated with greater belief in ETI,” the researchers reported, but ETI beliefs showed no correlation with supernatural beliefs or well-being beliefs.

From these studies the authors conclude: “ETI beliefs serve an existential function: the promotion of perceived meaning in life. In this way, we view belief in ETI as serving a function similar to religion without relying on the traditional religious doctrines that some people have deliberately rejected.” By this they mean the supernatural: “accepting ETI beliefs does not require one to believe in supernatural forces or agents that are incompatible with a scientific understanding of the world.” If you don't believe in God but seek deeper meaning outside our world, the thought that we are not alone in the universe “could make humans feel like they are part of a larger and more meaningful cosmic drama,” they observe.

Given that there is no more evidence for aliens than there is for God, believers in either one must take a leap of faith or else suspend judgment until evidence emerges to the contrary. I can conceive of what that might be for ETI but not for God, unless the deity is a sufficiently advanced ETI as to appear divine. Perhaps Captain Kirk has it right in his final reflections on God to the ship's doctor at the end of Star Trek V: “Maybe He's not out there, Bones. Maybe He's right here [in the] human heart.”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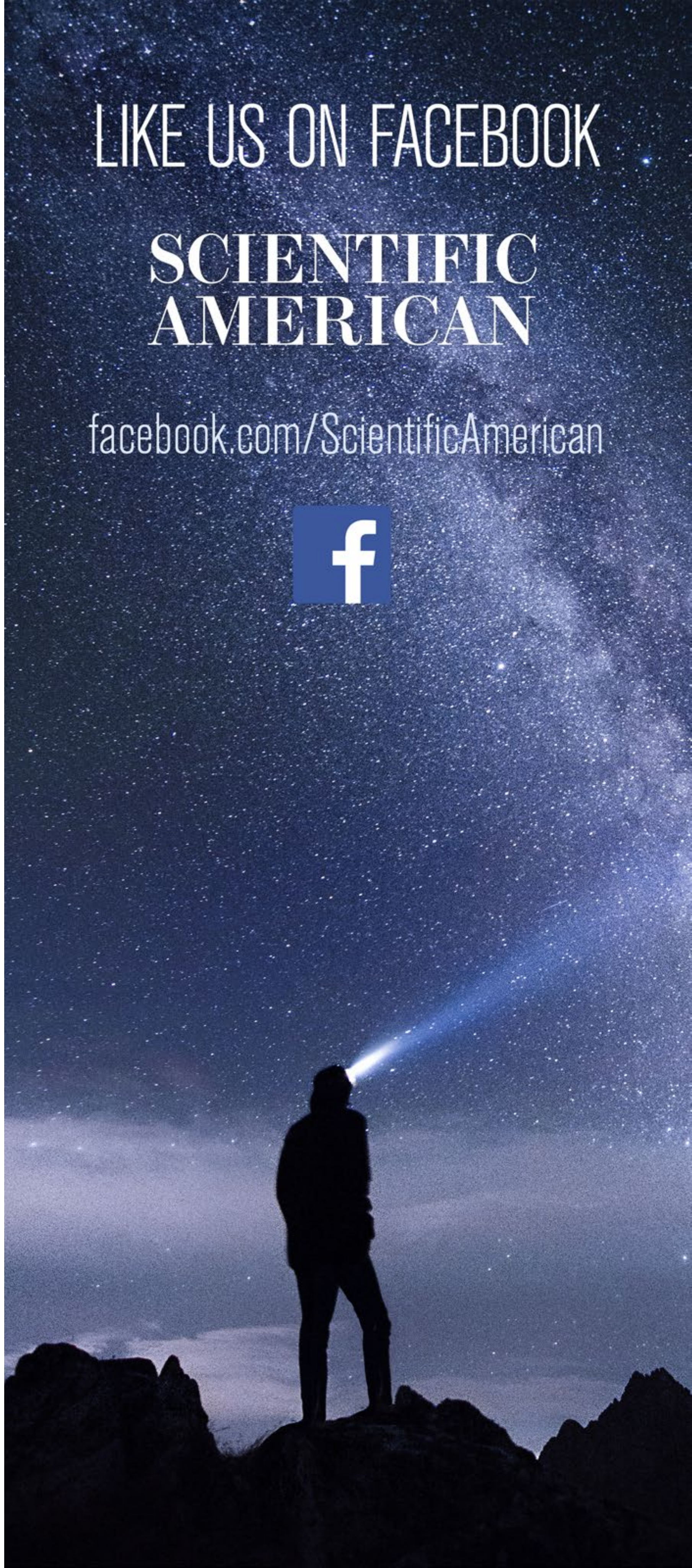

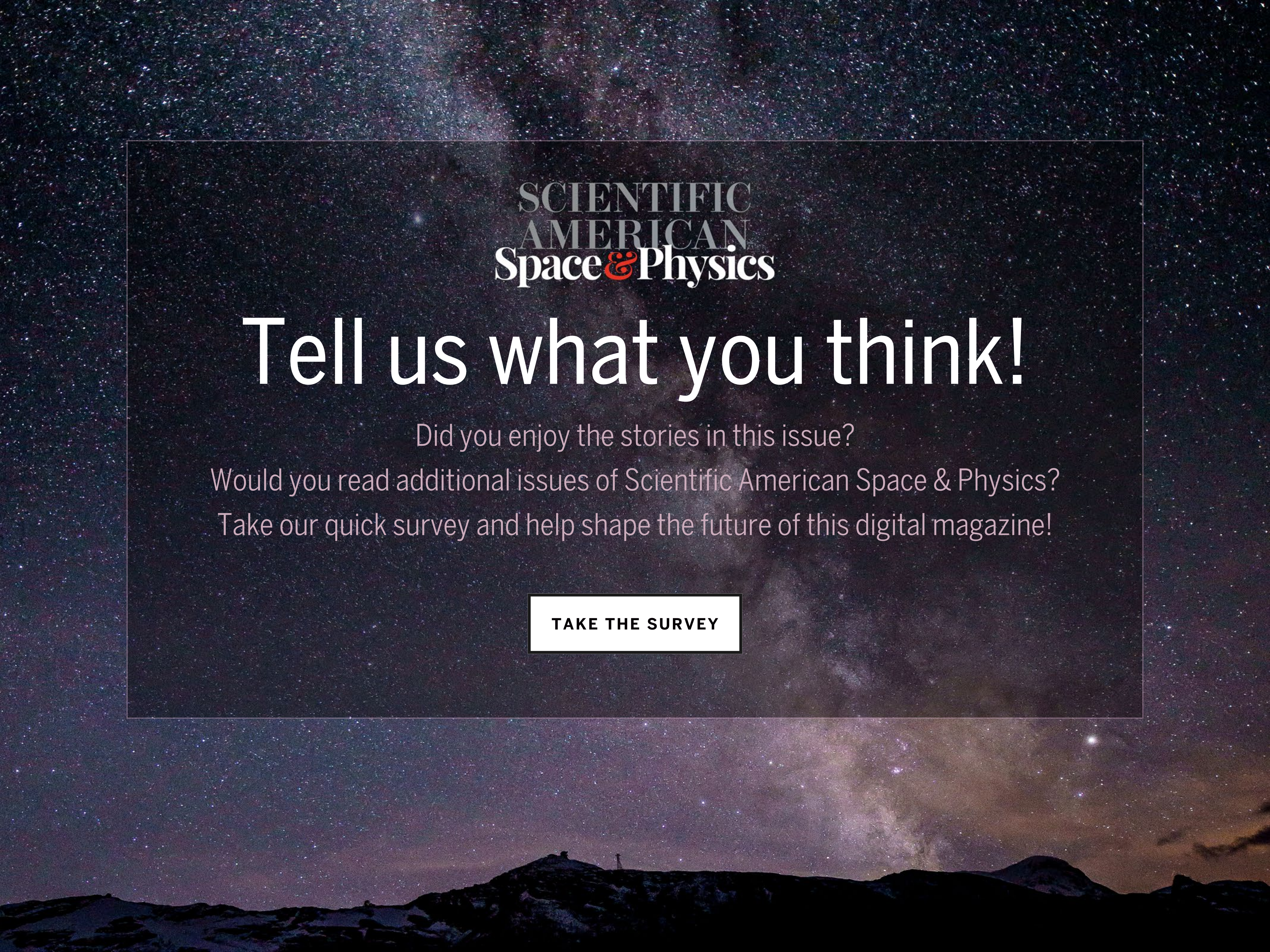

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