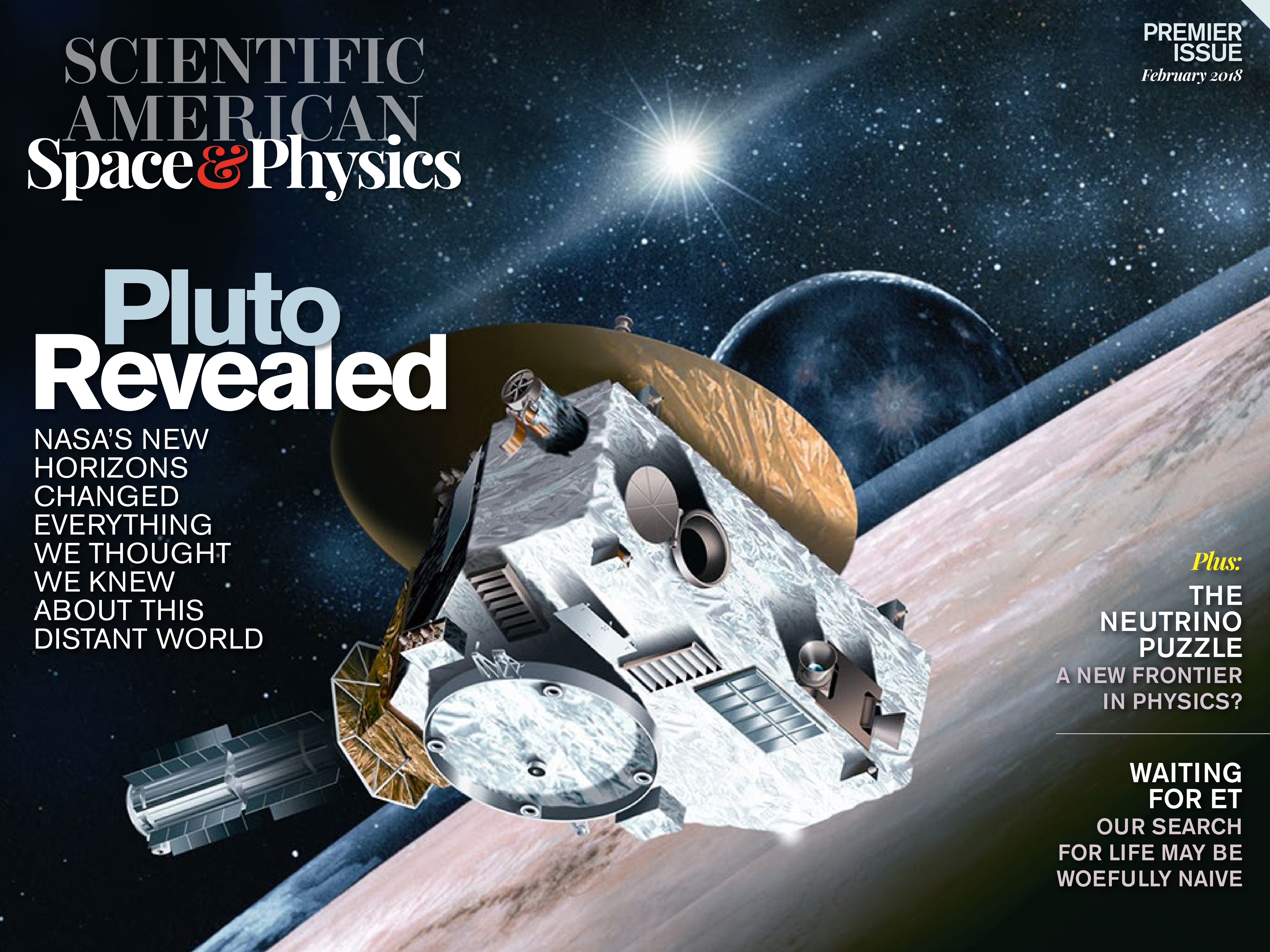

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Plus:

THE NEUTRINO PUZZLE

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WAITING FOR ET

OUR SEARCH FOR LIFE MAY BE WOEFULLY NAIVE

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PLUTO REVEALED

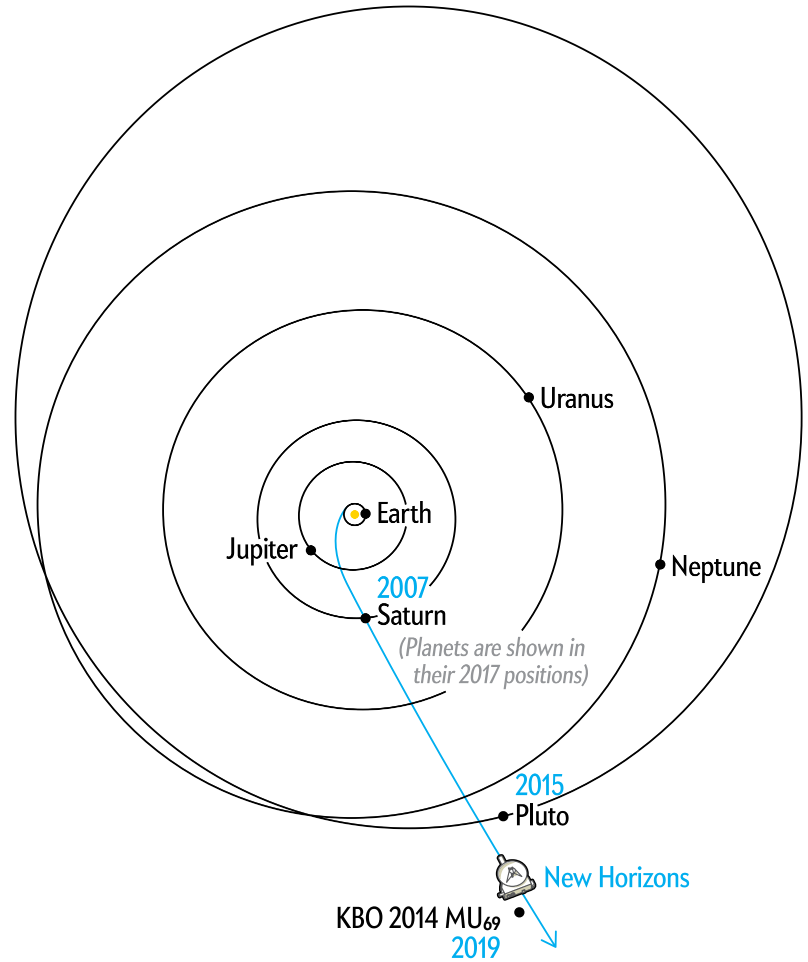
By S. Alan Stern

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.

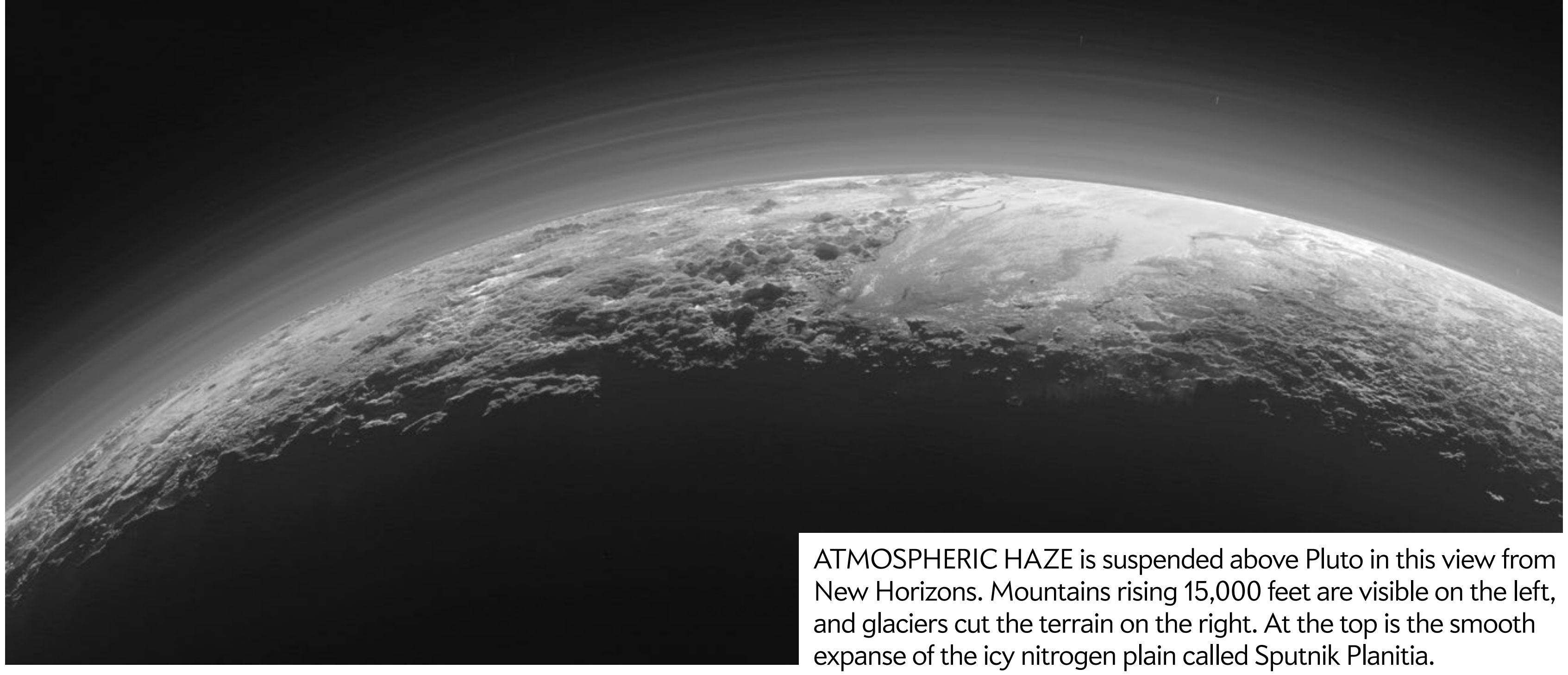
2001: A SPACE ODYSSEY

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.

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.



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

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.

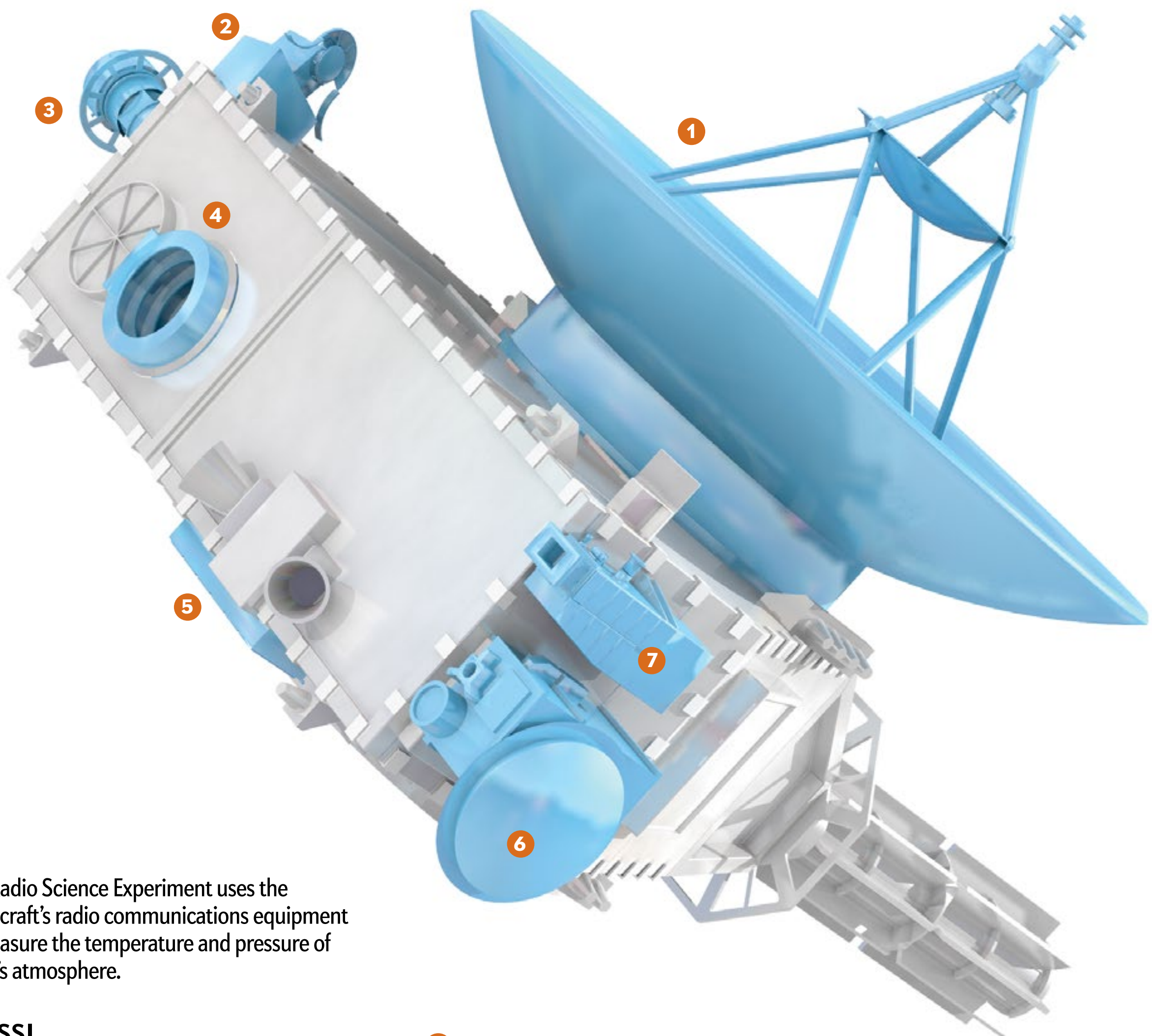
PLANNING A LONG-DISTANCE HOLE IN ONE

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.

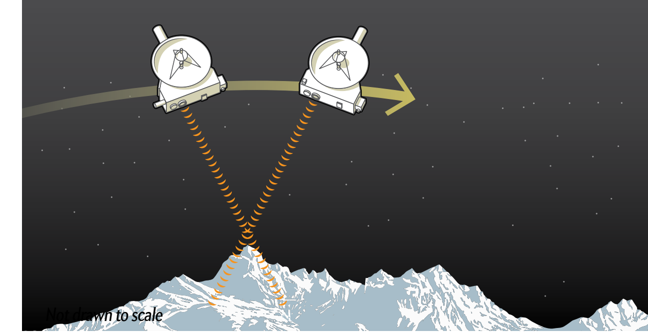
6 RALPH
This camera and spectrometer measures the wavelengths of incoming visible and infrared light to make color, composition and thermal maps of Pluto's surface.

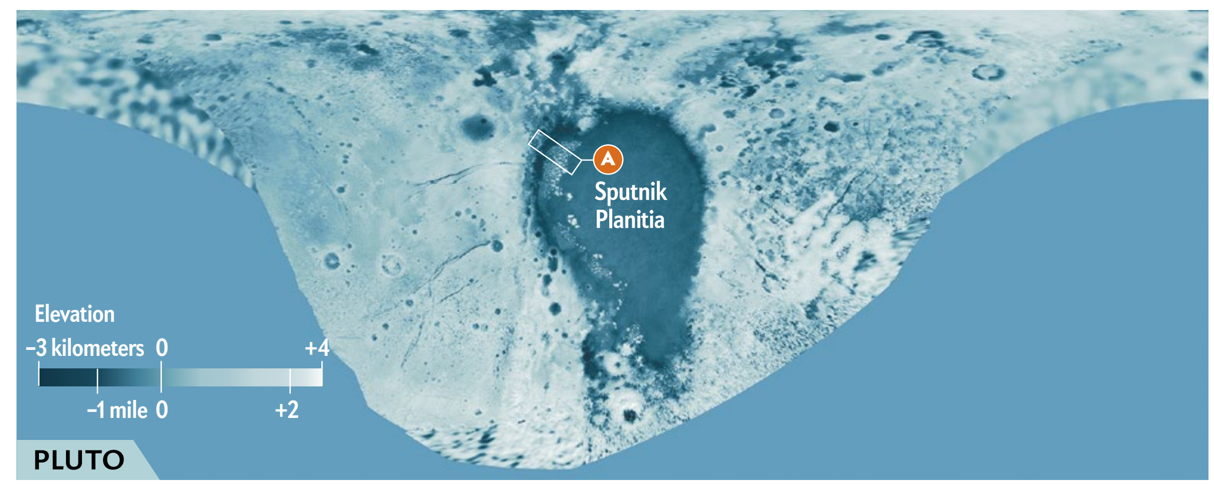
7 ALICE
Alice makes spectroscopic measurements of ultraviolet light to enable astronomers to study the makeup of Pluto's atmosphere and search for atmospheres around Charon and Kuiper Belt Objects.

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.





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.

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.

1

2

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).

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.