PLUTO SCIENCE UPDATE p. 28

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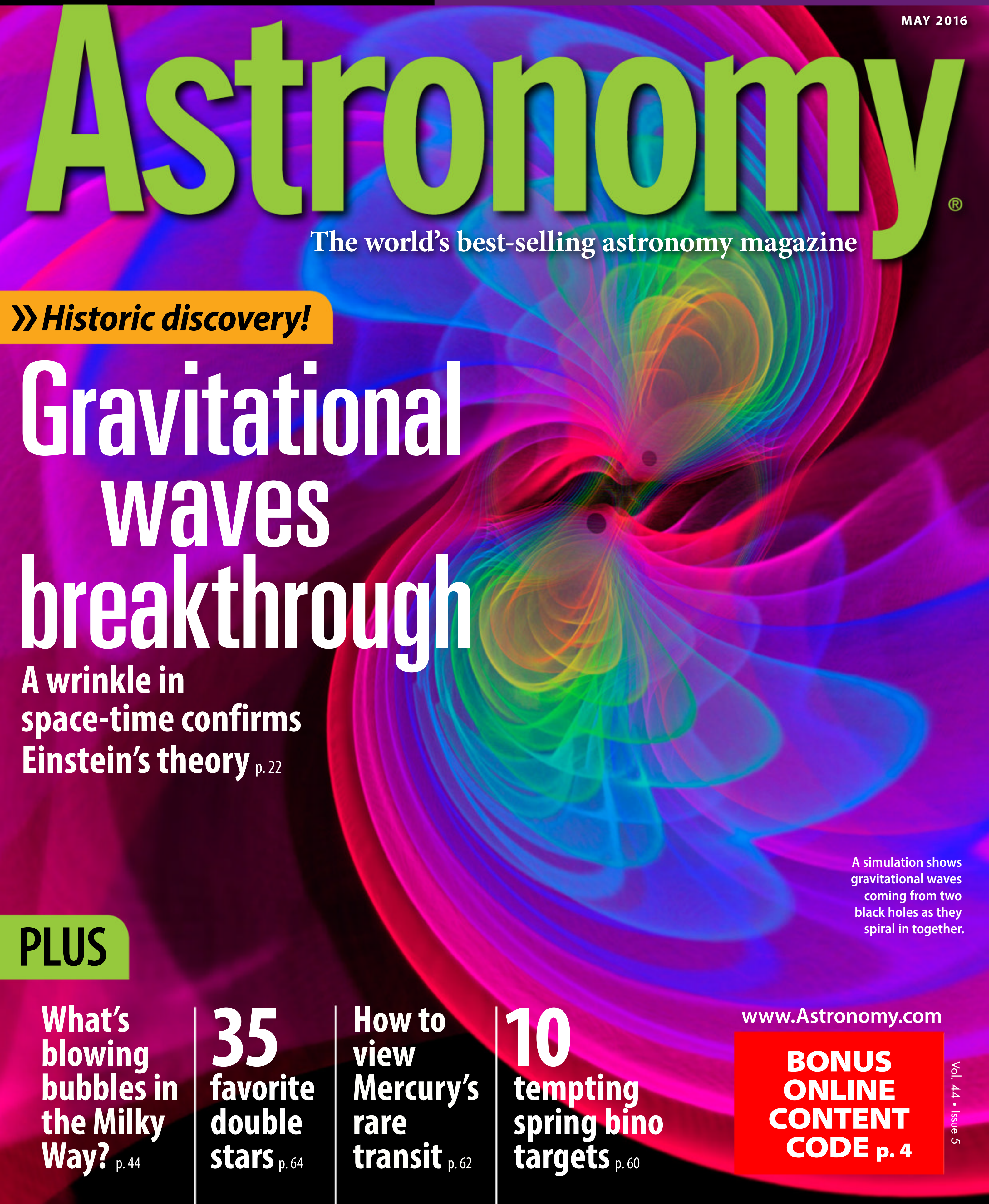

» *Historic discovery!*

Gravitational waves breakthrough

A wrinkle in space-time confirms Einstein's theory p. 22

A simulation shows gravitational waves coming from two black holes as they spiral in together.

PLUS

What's blowing bubbles in the Milky Way? p. 44

35 favorite double stars p. 64

How to view Mercury's rare transit p. 62

10 tempting spring bino targets p. 60

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BONUS ONLINE CONTENT CODE p. 4

Vol. 44 • Issue 5

HOT RESULTS from a COOL PLANET

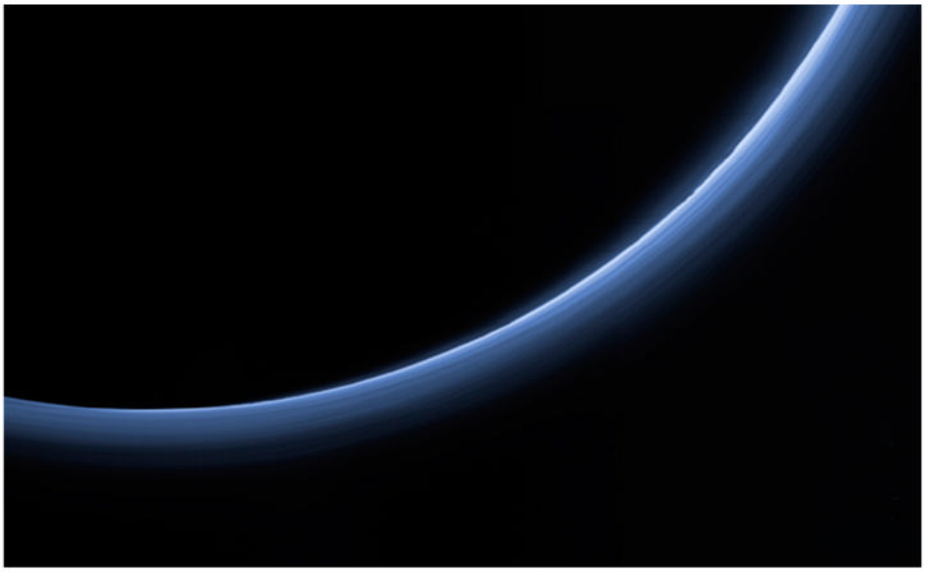
New Horizons reveals Pluto as a world of stark beauty and complex geology that has been active for billions of years. **by S. Alan Stern**

Last summer, NASA's New Horizons mission successfully and spectacularly completed the first exploration of the Pluto system. In just a matter of weeks, Pluto went from a point of light that could be studied only from afar to a planet in all its glory. And with this historic flyby, NASA and the United States concluded the reconnaissance of all the planets known at the time the Space Age began.

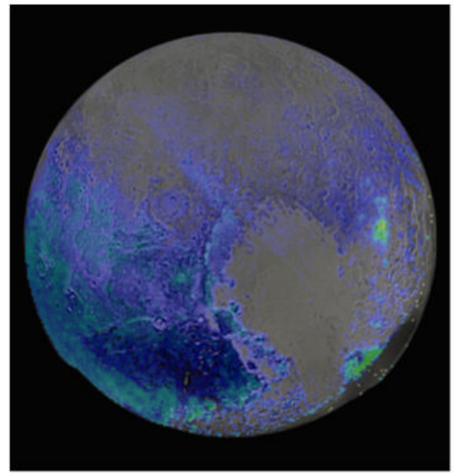
New Horizons collected a rich harvest of color and panchromatic images, spectra that mapped the surfaces at both ultraviolet and infrared wavelengths, and data on particles and plasma that has transformed our knowledge about Pluto and its five satellites. Chief among the findings so far: Pluto has been active over its entire 4.5 billion-year life; small planets can be just as complex as larger worlds like Mars; Pluto's big satellite, Charon, is much more complex than anyone had anticipated; and Pluto's four small moons display behaviors and attributes unlike any other small satellite system previously visited.

Now let's take a detailed look at many of the key discoveries that New Horizons made about Pluto and its family of moons.

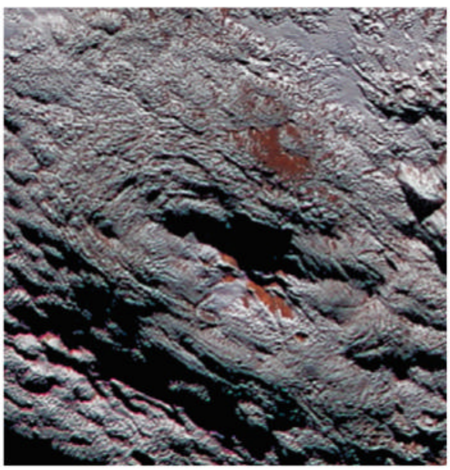
Pluto's geologic diversity stands out in this enhanced color mosaic taken when New Horizons was near closest approach. Scientists often exaggerate an image's color to highlight differences in composition and texture.
ALL IMAGES: NASA/JHUAPL/SwRI



Pluto's atmosphere glows a deep blue, rivaling the beauty of our planet's blanket of air. This nightside view reveals dozens of haze layers that extend up to altitudes of more than 125 miles (200 kilometers).



Water ice forms the "bedrock" of Pluto, with more volatile ices made of nitrogen, methane, and carbon monoxide coating the surface. This map traces the presence of water ice on the surface, with gray having none, blue a little, and green and yellow a lot.



The 90-mile-wide (150 kilometers) Wright Mons appears to be a shield volcano, like Hawaii's Mauna Loa or Mars' Olympus Mons, down to the deep central pit at its summit. Instead of lava, however, Wright Mons would erupt molten ice. All feature names used in this story are informal.

Pluto: icy wonderland

Pluto undoubtedly was the star of the show. It surprised us in more ways than I can count, from its sheer physical beauty to its complex geology, atmosphere, and remarkably varied surface composition. Let me summarize some of my personal favorites for the most important and surprising things the team has discovered so far. And just as a note, all the feature names I mention in this article are still informal ones given by the New Horizons team.

Sputnik Planum — a geologically active impact basin. We first spotted Sputnik Planum (SP), which forms the western half of Pluto's heart-shaped Tombaugh Regio, from more than 100 million miles (160 million kilometers) away, shining like a bright, highly reflective beacon on Pluto's surface. Close-up images later revealed that SP is a gigantic icy plain with a surface area of more than 350,000 square miles (900,000 square kilometers). Those images also revealed SP to be almost perfectly flat and ringed on all sides by mountains jutting 2 to 3 miles (3 to 4km) above its floor. This indicates that the Texas-sized feature may well be a gigantic impact basin formed by an ancient collision between Pluto and a large Kuiper Belt object perhaps 60 to 125 miles (100 to 200km) across.

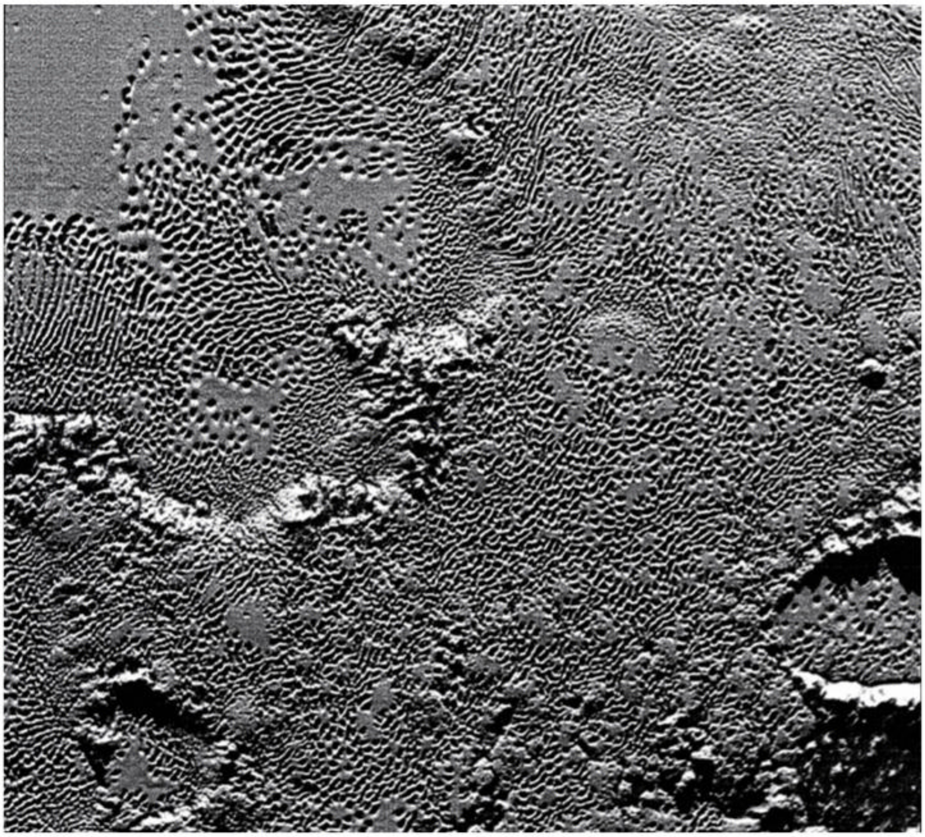
But there's more to SP than its impact origin. The central and northern regions of this expanse display a cellular pattern in the ices, with characteristic cell sizes of 30 to 60 miles (50 to 100km). The cells are bounded by shallow troughs up to 330 feet (100 meters) deep. The southern region and eastern margin of SP do not display this cellular morphology. Instead, these areas appear to be featureless plains with myriad pits up to a few miles long that we interpret to be the result of sublimation, ice turning directly into a gas.

We have not found a single crater anywhere on SP down to the limit of our highest-resolution images, at 230 feet (70m) per pixel. Calculations show that this means the surface is less than 10 million years old. We interpret this young age and the cellular nature of northern and central SP as evidence for thermal convection in its deep ices, but where the energy that drives this heat flow arises remains unclear.

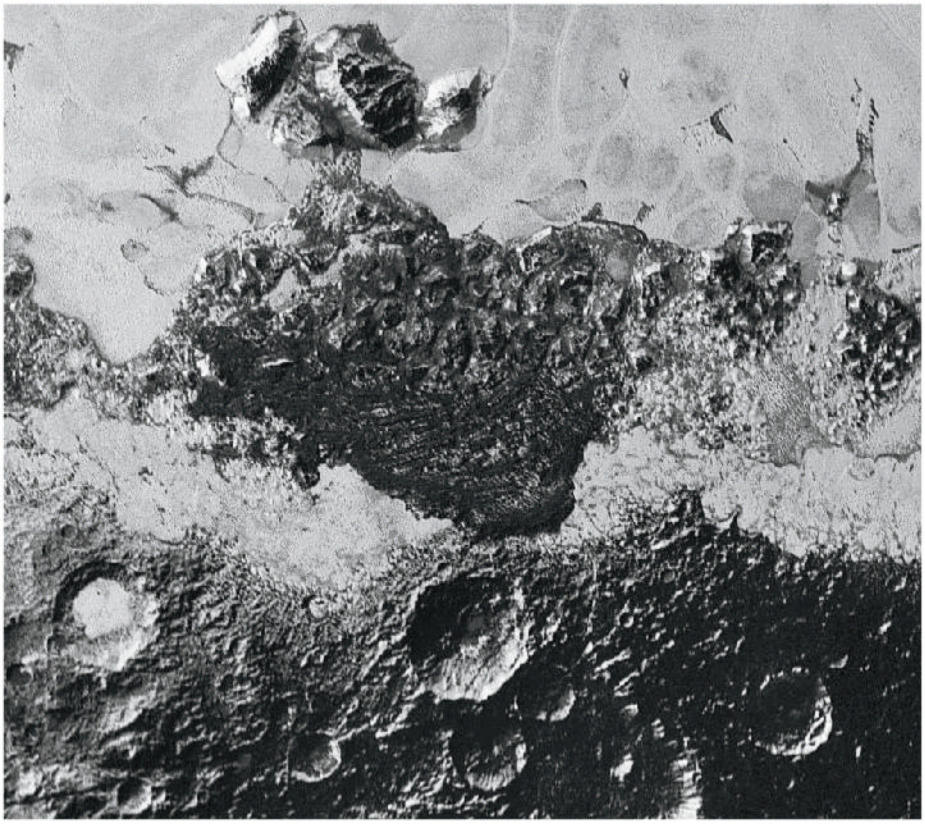
A cold and hazy atmosphere. One of New Horizons' major objectives was to study Pluto's blanket of air. Although scientists had discovered this feature from Earth in the late 1980s, New Horizons upended many of our ideas. For example, it found the upper atmosphere to be tens of degrees colder than expected; prior to the flyby, we thought it was warm enough to drive a prodigious atmospheric escape rate that rivaled those of comets. Instead, we uncovered a very Earth-like escape rate, about 100 to 1,000 times slower than predicted.

And whereas Earth-based experiments stretching over almost two decades had failed to find evidence for hazes and discrete cloud layers in Pluto's atmosphere, New Horizons found both. The team has counted more than two dozen haze layers in New Horizons images that stretch up to altitudes higher than 125 miles (200km) above Pluto's surface. These hazes likely form photochemically as ultraviolet light interacts with the nitrogen, methane, and carbon monoxide that dominate the atmosphere's composition. These haze particles grow to sizes of about 0.1 to 0.5 micron across and eventually silt out of the atmosphere onto the surface. Seen in color at sunset, the haze scatters sunshine and creates a blue tint that produces hauntingly beautiful images of blue skies on a faraway planet. And in a bonus for mapping purposes, we found the hazes cast sunlight hundreds of miles across onto Pluto's

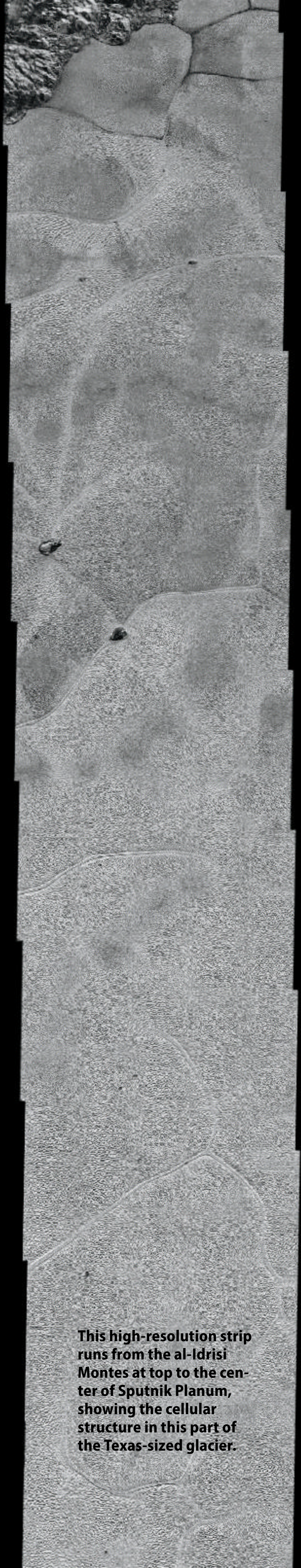
S. Alan Stern *of the Southwest Research Institute in Boulder, Colorado, is a planetary scientist and the principal investigator on the New Horizons mission.*



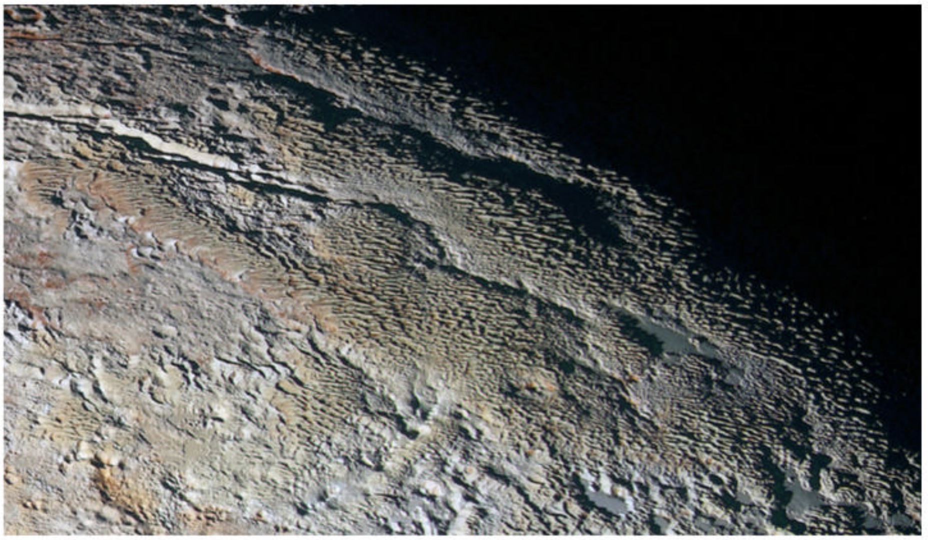
The southern part of Sputnik Planum resolves into myriad pits in this high-resolution image taken when New Horizons was just 13 minutes from closest approach. Scientists think the pits arise as ice turns directly into gas.



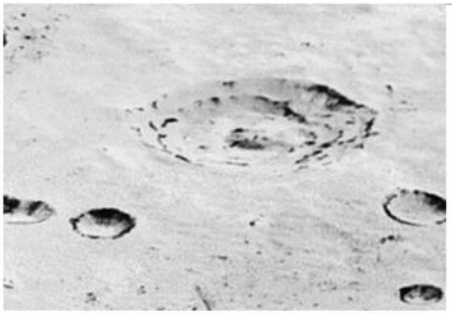
The ancient, heavily cratered Cthulhu Regio at the bottom of this image appears to be more than 4 billion years old, yet it lies adjacent to the ice-rich plains of Sputnik Planum at top, which likely is less than 10 million years old.



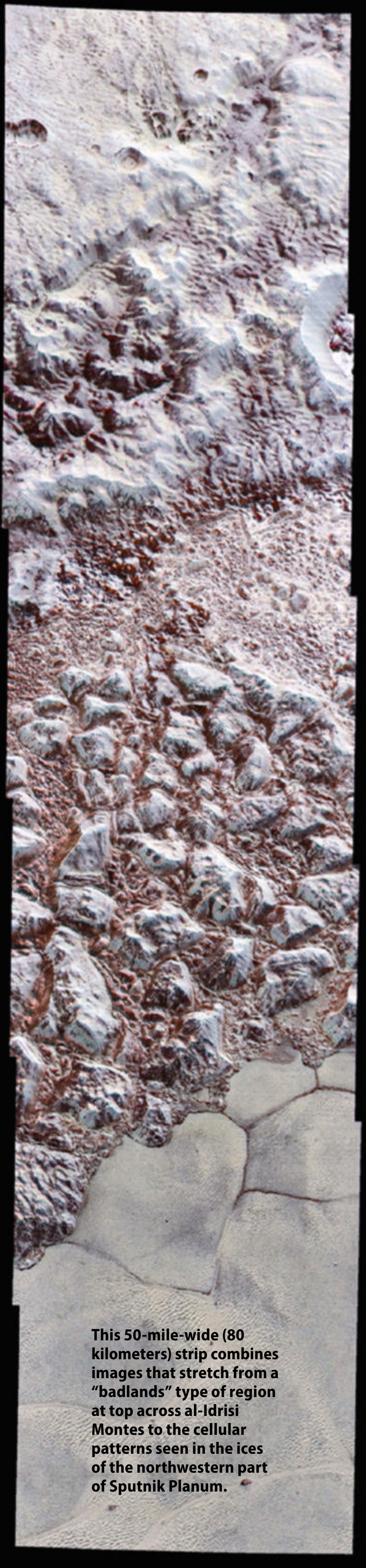
This high-resolution strip runs from the al-Idrisi Montes at top to the center of Sputnik Planum, showing the cellular structure in this part of the Texas-sized glacier.



As New Horizons swept by Pluto, it captured this view of the oddly textured mountains called Tartarus Dorsa along the day-night terminator. Scientists don't know what causes the snakeskin-like terrain.



Distinct layers show up in several of the craters in this image, most noticeably the one above center. Typically, such layers indicate either a change in composition or the rate at which material was deposited, but scientists don't know yet what caused these features on Pluto.



This 50-mile-wide (80 kilometers) strip combines images that stretch from a "badlands" type of region at top across al-Idrisi Montes to the cellular patterns seen in the ices of the northwestern part of Sputnik Planum.

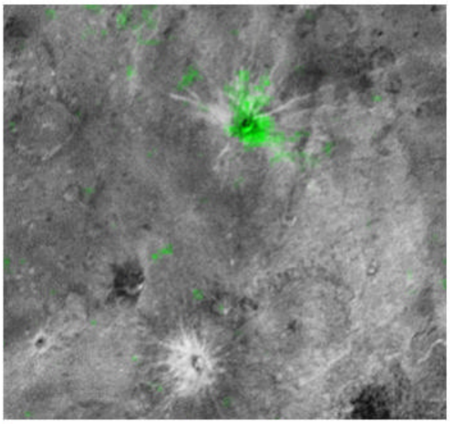
nightside, allowing us to use "hazeshine" to map terrains we never thought we'd see at close-approach resolution.

Activity across billions of years. Although SP has an estimated age of just 10 million years (much less than 1 percent the age of the solar system), other regions on Pluto have strikingly different ages. West of southern SP lies Cthulhu, a region that is large, dark, and volatile-poor (meaning it lacks substances that vaporize at relatively low temperatures). Cthulhu contains some of the most heavily cratered and ancient terrains on Pluto. We have dated these rugged areas at more than 4 billion years — the ancient opposite of SP!

Even more amazing are terrains on the eastern lobe of Pluto's heart. This region, known as Eastern Tombaugh Regio, has an intermediate age of just 1 billion years. Together, SP, Cthulhu, and Eastern Tombaugh Regio paint the picture of a planet that has been geologically active throughout its entire 4.5 billion-year history. We still don't know how a small planet like Pluto powers such activity over such an expanse of time.

Tectonics, and volcanoes, too? The hemisphere New Horizons saw best at closest approach shows numerous extensional tectonic features — those that form as the surface spreads apart — in varying stages of degradation. Most dramatic is the 2- to 3-mile-deep (3 to 4km) V-shaped trough we call Virgil Fossa, which runs unbroken for more than 125 miles (200km). Numerous other tectonic features testify to past geologic activity on Pluto. But even more dramatic and surprising was the discovery of two 95-mile-wide (150km) mountains with deep central pits at their summits. These features, called Wright Mons and Piccard Mons, bear a strong structural resemblance to shield volcanoes such as Mauna Loa and Mauna Kea on Hawaii. The lack of craters on their flanks suggests they have been active in the past billion years. No such large volcano-like features have been seen anywhere else in the solar system except among the inner planets!

Layering in Pluto's surface. High-resolution images of Pluto's surface also reveal distinct layering in some places. We first detected this exciting and unexpected feature in the large mountain blocks of al-Idrisi Montes. But the science team later found more layering inside craters and canyons to the northwest of these mountains. Are we seeing variations in the composition of Pluto's crust with depth? Or are we seeing the result of time variations in the sedimentation rate of atmospheric soot? We do not know.



▲ The ammonia-rich ejecta (shown in green) that surrounds the impact crater Organa on Charon shows it to be a relatively young feature. Compare its ejecta with that surrounding Skywalker Crater below, which, like the rest of the moon, is rich in water ice.

◄ Pluto's large moon, Charon, sports a dark reddish polar region as well as a network of fractures and chasms that spans at least 650 miles (1,050 kilometers) across the equatorial region of its Pluto-facing hemisphere.

Water, water everywhere. As soon as the science team saw steep mountains and canyons on Pluto in the earliest high-resolution images, we knew this implied that the planet's crust is made of water ice, as we had expected. We knew this because the volatile nitrogen, methane, and carbon monoxide ices across Pluto's surface that scientists had detected from Earth are too weak to support such steep topography. So, knowing that water ice is common across the outer solar system, and having inferred its presence indirectly from measurements of Pluto's interior density that indicated up to one-third of the planet's mass was H_2O, we felt pretty confident of the water-ice crust prediction.

High-resolution compositional spectroscopy later vindicated that expectation when it revealed many places on the surface where water ice is directly exposed. Although it remains a mystery as to why Earth-based telescopes never spotted these signs, the signatures of water ice are unmistakable. Pluto's water-ice crust peeks out at hundreds of locations across its disk.

Charon: multifaceted moon

New Horizons confirmed some of our expectations about Charon. These include the moon's diameter — 754 miles (1,214km) — which is barely different from ground-based measurements, the lack of exposed volatile ices on the surface, and no evidence of any atmosphere. But close-up data revealed many other details about Charon that have enriched its story and make it an amazing world in its own right.

Perhaps chief among these is the wide variety of geologic features on Charon's surface. From heavily cratered terrains in the northern hemisphere to ice-flooded terrains indicating a complex early history in the south, Charon clearly was geologically alive at some point. The surface also displays strange pitted terrains, bright- and dark-rayed craters, and an equatorial extensional tectonic belt so large that it dwarfs the Grand Canyon and rivals anything else in the solar system except Valles Marineris on Mars. The science team thinks that Charon once might have had a subsurface ocean of water; when it froze, the surface expanded and created the system of faults.

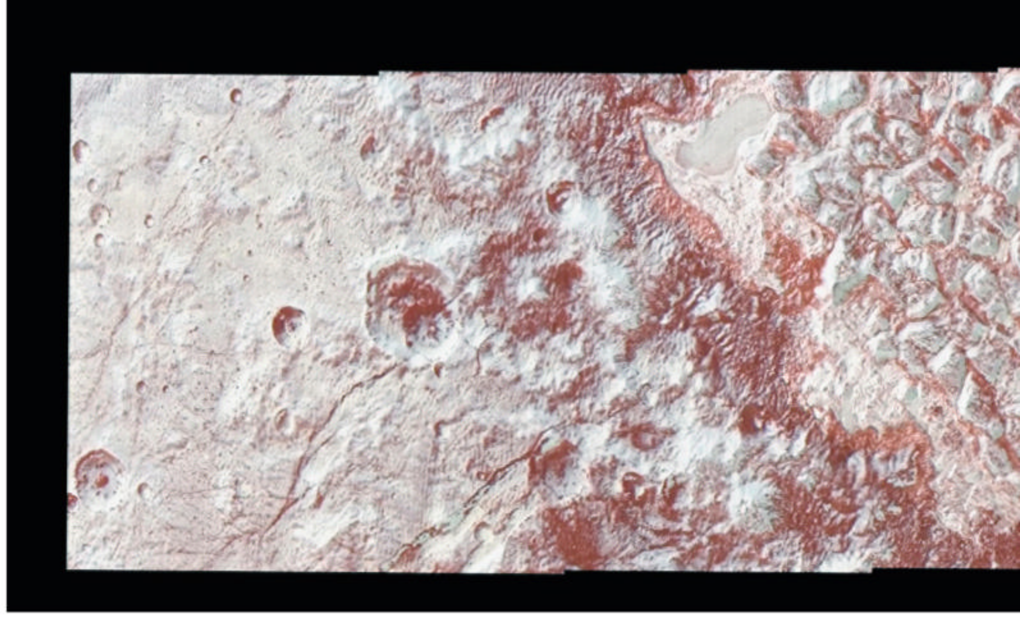
Strangely, however, we have dated all of the terrains on the hemisphere we viewed at closest approach to about 4 billion years or older, meaning all these features were born more or less together in a brief flurry of internal activity shortly after Charon itself formed.

We also found deposits rich in ammonia peeking out of some craters and low-level concentrations of ammonia or ammonium hydrates scattered widely across Charon's predominantly water-ice surface. No ammonia-rich terrains are seen on any other icy satellite in the solar system. Why Charon alone sports this unique compositional telltale is a mystery.

Another enigma is wrapped up on Charon's north pole, which sports a dark reddish cap a few hundred miles across. High-resolution images reveal that these dark red polar deposits are apparently a stain draped over the pole's topography. A leading theory for this material's formation is that it originated as volatile substances that were transferred from Pluto's atmosphere and condensed on Charon's cold polar terrains. Radiation exposure then darkened and reddened it into non-volatile hydrocarbons and heavier molecules called tholins. If this idea is correct, then Charon's south pole — hidden from us at flyby — should sport a similar stain. No doubt future space missions to Pluto will be eager to check this out, for that also could confirm a long-held speculation that Pluto's atmosphere sometimes expands sufficiently to be shared by Charon.

Small satellite shockers

Pluto's smaller moons also provided real surprises. Between 2005 and 2012, New Horizons team members discovered four small satellites using the Hubble Space Telescope. We named them Styx, Nix, Kerberos, and Hydra in order of their distance from Pluto. New Horizons imaged all four during the flyby and found them to range in size from about 6 miles (10km) to about 30 miles (50km) across. We expected to find still more satellites when we got closer to Pluto, and we searched for them



NEW HORIZONS: CURRENT AND FUTURE PLANS

New Horizons is now several astronomical units (AU; one AU is the average Earth-Sun distance, about 93 million miles or 150 million kilometers) past Pluto, plunging ever deeper into the Kuiper Belt. The spacecraft is healthy and operating on its primary systems, with backup systems still held in reserve.

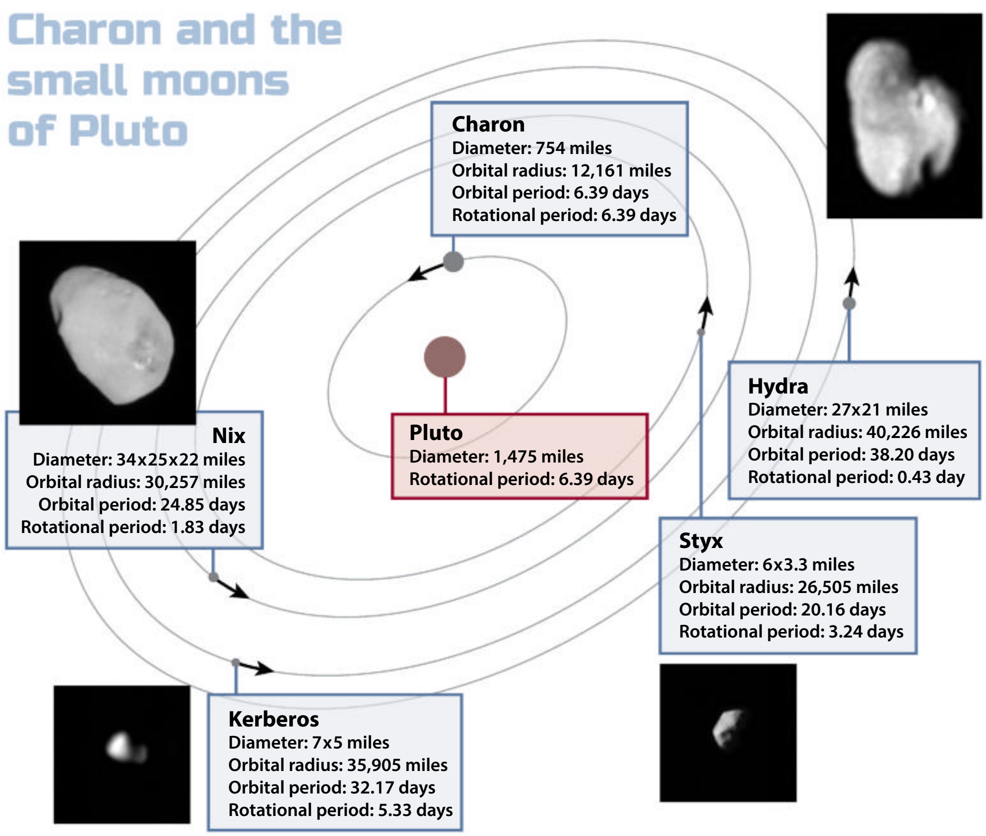
The New Horizons team designed the spacecraft to function out to at least 55 AU from the Sun, a distance it won't reach until late 2022, and there is no reason that it can't actually operate much farther out than that. In fact, if the vehicle remains healthy, our flight team believes we have the power and fuel to keep going into the mid-2030s, at which point New Horizons will be near the 100 AU distance marker, about where Voyager began to cross the heliopause and escape the Sun's magnetic influence.

In late October and early November 2015, with NASA's go-ahead, our mission team conducted a series of four engine burns to send New Horizons toward a new Kuiper Belt object (KBO). The flyby target, discovered by the Hubble Space Telescope in a search performed for New Horizons, is called 2014 MU_{69}.

This object is about 25 miles (40km) across and circles the Sun on an orbit 44 AU away. It is a "cold classical" KBO, meaning it almost certainly formed near where it is now and contains valuable information about the chemical and physical environment of the ancient Kuiper Belt. In fact, 2014 MU_{69}, which the Sun has never warmed above temperatures of about 50 to 60 kelvins, is the most primitive specimen of the early solar system ever targeted by any space mission.

On January 1, 2019, New Horizons will pass very close to MU_{69} — much closer than we flew by Pluto — where we can study its geology and composition, search for and study any small satellites it may have, and hunt for evidence of a comet-like coma.

We have proposed the flyby exploration of MU_{69} as the centerpiece of an extended mission for New Horizons lasting into 2021. That mission is called the New Horizons KBO Extended Mission, or KEM. In addition to the MU_{69} close flyby, KEM also proposes to gather other kinds of unique and valuable Kuiper Belt science that can't be obtained from Earth or Earth orbit. These would include close-in satellite searches and photometry for another 20 or so small KBOs, and studies of the plasma, neutral gas, and dust environment of the Kuiper Belt out to 50 AU. NASA expects to let us know if KEM is approved and funded by this summer. — *S. A. S.*

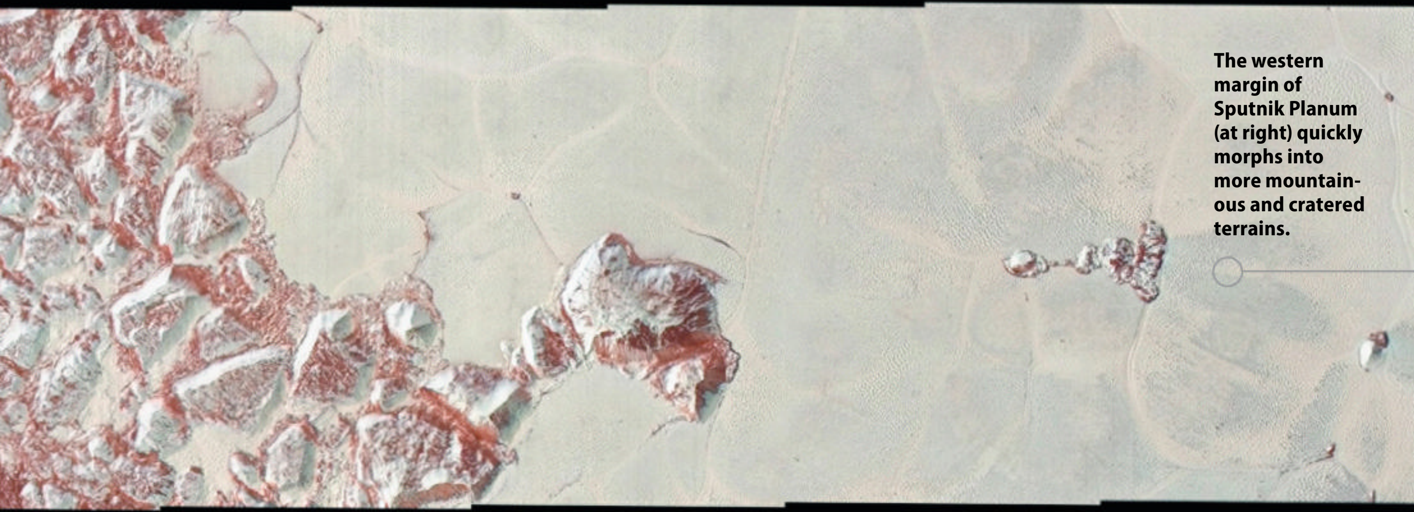


Close-in Charon, which is tidally locked to Pluto, is by far the planet's largest and best-studied satellite. In contrast, the four small outer moons all rotate faster than they revolve around the planet, making this satellite system unique in the solar system. These moons also are far more reflective than scientists expected, and two of them — Styx and Hydra — appear to have formed from the mergers of two even smaller moons. (To convert miles to kilometers, multiply by 1.61.) *ASTRONOMY*: ROEN KELLY

long and hard. But we didn't find any down to sizes of just 1 or 2 miles (2 or 3km) across. This was a big surprise — but it wasn't all.

We also found that while all four of the small moons are elongated, the quartet seems to break into an inner and outer pair, each containing one small and one larger satellite. At least two of them — Styx and Hydra — appear to be bilobate, as if they formed from mergers of still smaller moons that once orbited Pluto. Nothing like this has been found anywhere else among the planets.

Perhaps even more puzzlingly, though, images of the small satellites show that they all reflect much more light than we'd expected. Rather than showing a surface

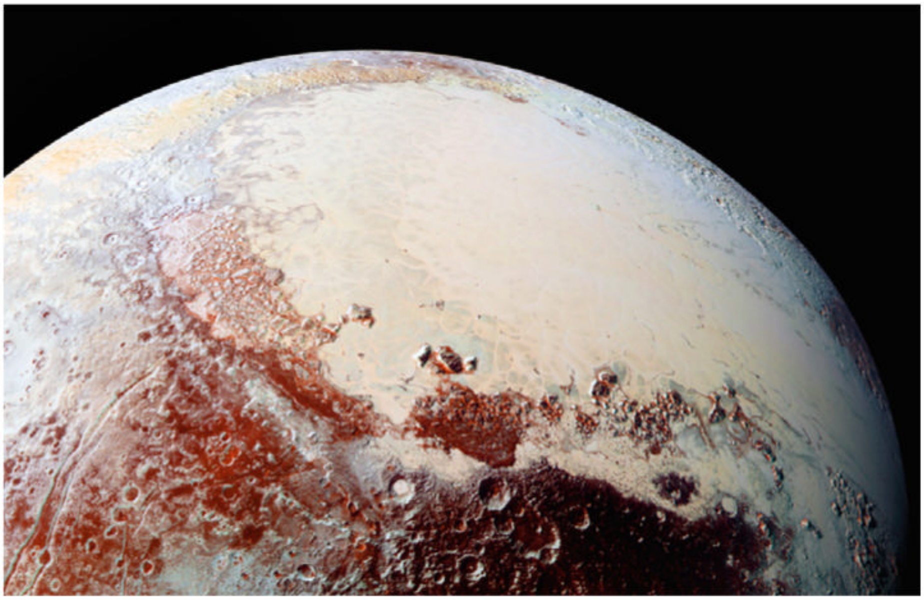


The western margin of Sputnik Planum (at right) quickly morphs into more mountainous and cratered terrains.

reflectivity similar to Charon's, about 35 to 40 percent, they all have reflectivities closer to 70 to 80 percent. In fact, somehow all four are, on average, more reflective than Pluto! We suspect this happens because each moon has a bright, icy surface, and we'll find out for sure later this year when we get compositional spectra of them to the ground. But whether they are icy or not, we do know that all four must be pelted by cometary debris from the Kuiper Belt. And that debris, if similar to comets, must be very dark. So why aren't Pluto's four small companions dark after this rain of impactors? It's a mystery.

We also don't understand the rotation rates for these small worlds. It turns out that all four rotate much faster than their orbital periods. Conventional wisdom, backed up by dynamical calculations, predicted that each one should be tidally locked to Pluto so that its rotation period matches its orbital period (which range from 20 to 38 days). Charon has done so, but its smaller siblings have not. Their rotation periods range from 5.3 days down to just 0.4 day — that's just 10 hours!

What keeps these rotation rates so high? Again, we don't know. We also don't know why all four have rotation poles that are oriented 80° or more from the poles of Pluto and Charon. Both their rapid rotation and this puzzling dynamical configuration have sent orbital dynamicists back to the drawing board. As with just about everything else in the Pluto system, we are amazed, we are surprised, and we remain puzzled.



This perspective view shows what you would see from 1,100 miles (1,800 kilometers) above Pluto's equator. The view looks northeast over the dark, cratered Cthulhu Regio toward the smooth, bright, icy plains of Sputnik Planum.

Pluto needs an orbiter

The long-anticipated exploration of Pluto and its system of moons is at long last complete. And although data will continue to come to Earth for many more months, no doubt bringing new surprises, some things already are clear. Chief among them is the complexity of Pluto's story — from the origin of its satellites to the perplexing degree of expression in the surface geology to the even more mystifying ongoing geologic activity we see on the planet's surface.

But the mysteries don't stop there. Both Pluto's atmospheric structure and how it generates those haze layers are puzzling, as is the complex interaction among the glacier-like movement of snows on the planet's surface, the atmospheric dynamics, and many of the landforms across the globe. Everywhere we look to solve mysteries in the data sets we have, we find we need more data.

We need to see beneath the surface. We need to see how the planet evolves from season to season. We need thermal maps, and we need still-higher-resolution imagery. We also need direct measurements of Pluto's winds and the composition of its atmosphere and haze. And we long for higher-resolution maps that reveal the hemispheres of Pluto and its satellites that New Horizons saw only from afar.

Put simply, the Pluto system has revealed itself to be too complex to unravel with a single flyby, even one with the sophisticated instruments that New Horizons carried. We need an orbiter. The buzz for this is already alive and growing in the scientific community, and every time I give a public talk, I hear laypeople asking when we will go back. It won't be long, I predict, before studies of just such a mission will be on drawing boards.