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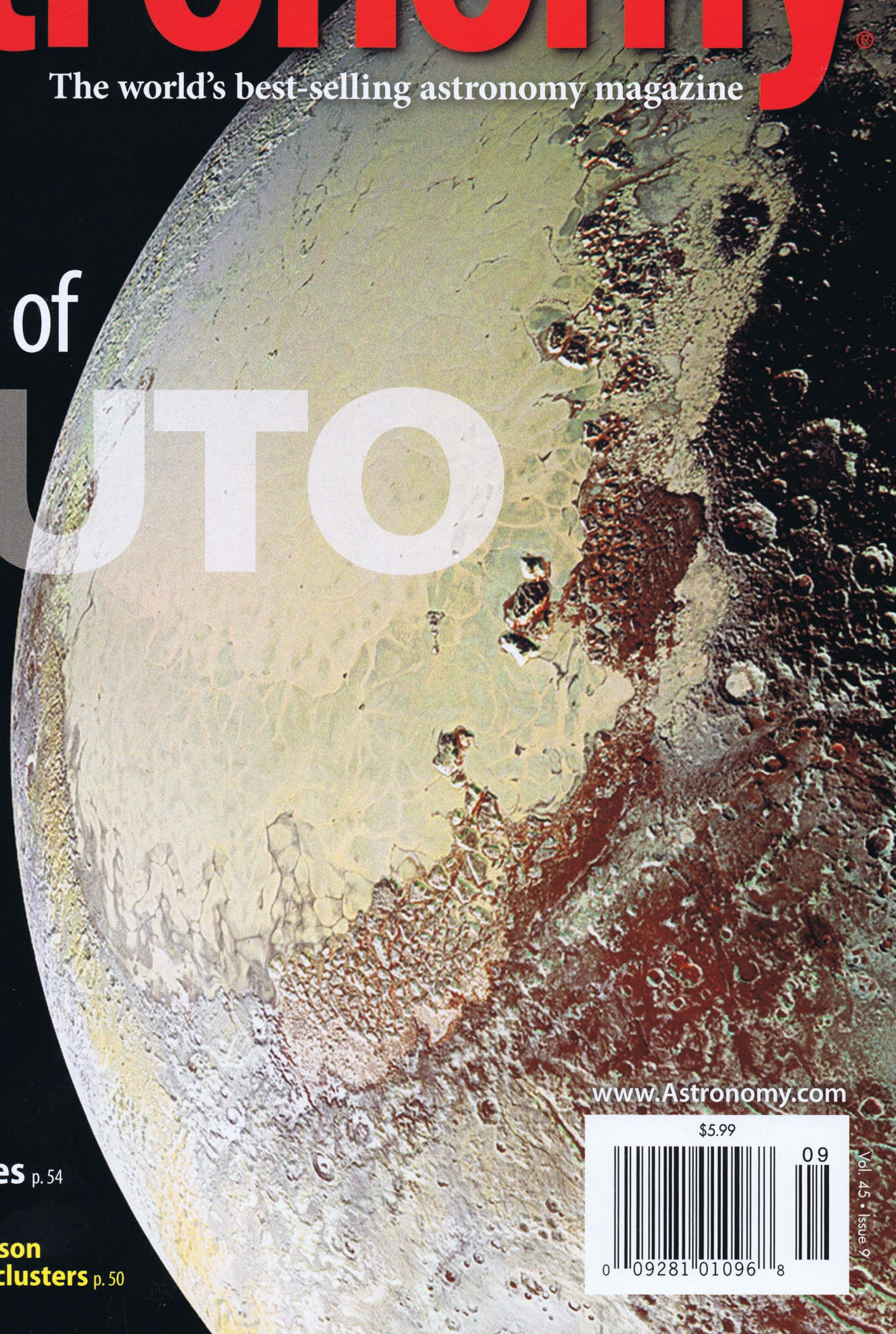

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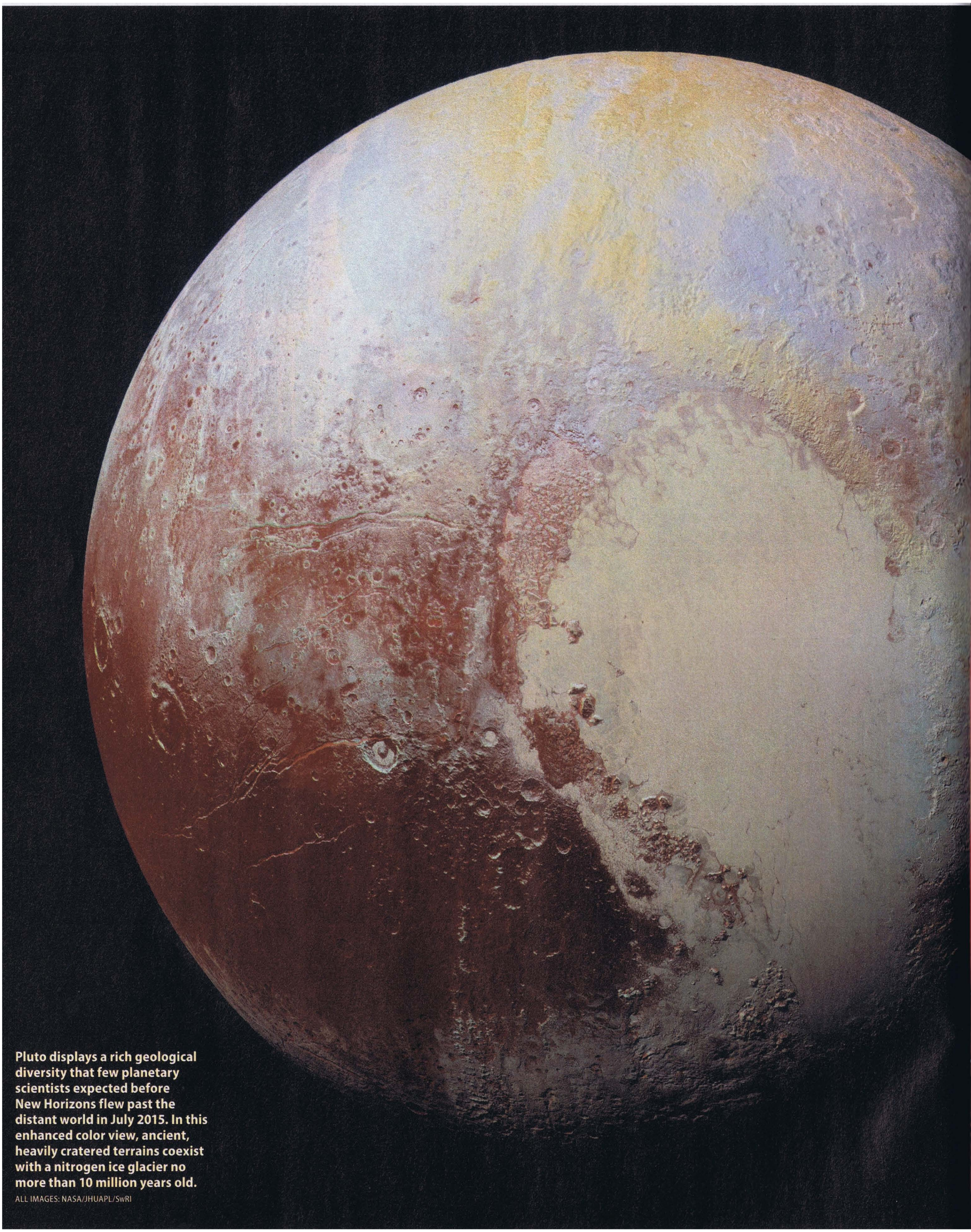
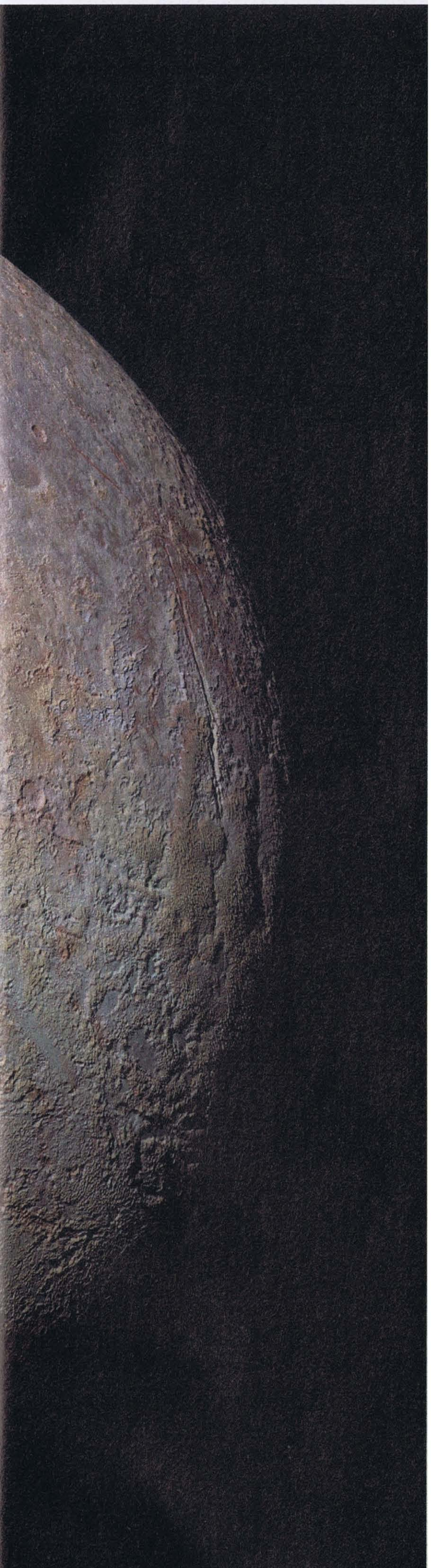


Pluto displays a rich geological diversity that few planetary scientists expected before New Horizons flew past the distant world in July 2015. In this enhanced color view, ancient, heavily cratered terrains coexist with a nitrogen ice glacier no more than 10 million years old.

ALL IMAGES: NASA/JHUAPL/SwRI



Far from the inert ball of ice some scientists expected, this distant world boasts unique landscapes, recent geological activity, and a possible underground ocean. **by S. Alan Stern**

The exploration of Pluto by NASA's New Horizons spacecraft revolutionized our knowledge of this small planet and its system of five moons. But it also did much more. The encounter showed us again that there is no substitute for going to the planets to learn about them, and it proved once more how first flybys thoroughly shatter scientific paradigms.

Every time we used the cameras, spectrometers, and other onboard sensors on New Horizons, we made discoveries about the Pluto system. We found that the planet's four small moons — Nix, Hydra, Kerberos, and Styx — are as old as Pluto itself, and all are covered in water ice that somehow is kept clean or is eternally refreshed to produce astonishingly high surface reflectivities. We also learned that these satellites surprisingly rotate much faster than they orbit Pluto, and that they are not accompanied by still more small moons as many of us had expected.

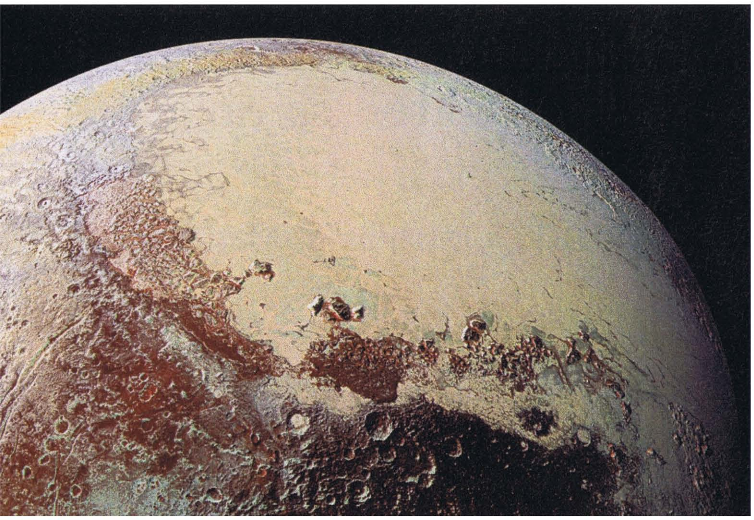
Pluto's giant moon, Charon — the other member of the binary planet at the heart of the Pluto system — also surprised us. It displays an old surface sporting a dark, red northern polar cap unlike anything seen elsewhere in the solar system, flooded plains of water ice, and vast extensional tectonic features — which form under stress as the moon's surface spreads apart. Charon even shows evidence of a possible internal ocean in its youth.

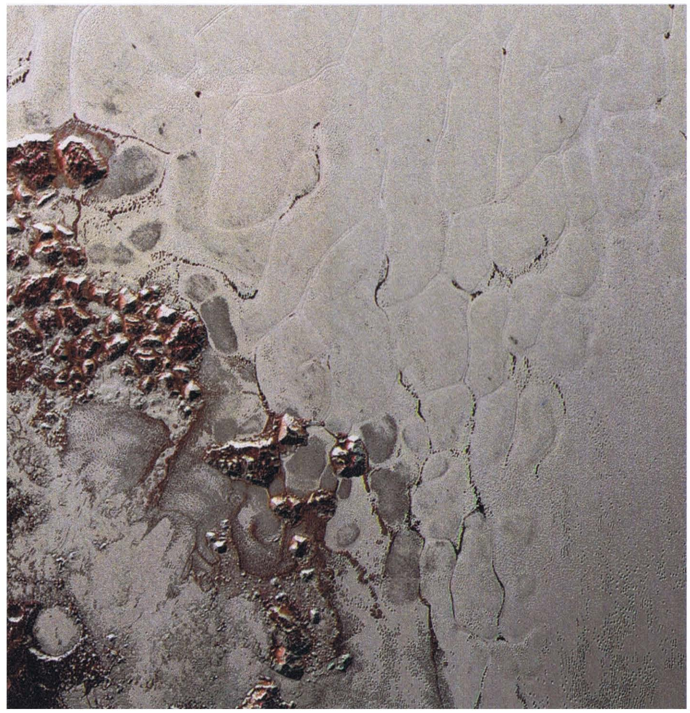
And then there is Pluto — geologically alive on a vast scale and displaying a range of landforms that rivals Mars, the solar system's other red planet. No one really expected any of these big-ticket Pluto surprises. And few anticipated the complexity we see in Pluto's suspended haze layers, the blue color of its sky, the almost 1,000-times lower atmospheric escape rate than predicted, or the evidence seen on the surface that Pluto's atmospheric pressure has been, apparently, sometimes tens to thousands of times higher than what we see today. Yet we found all of this, and much, much more.

The entire data set from New Horizons is now on Earth, and is archived in the open-access NASA Planetary Data System. Researchers on our science team have examined all of the 400-plus observations made by our seven scientific instruments and written over 50 technical papers detailing early findings. But there is much more to do to understand Pluto, and to extend those findings to a better understanding of the other small planets in the Kuiper Belt.

In *Astronomy*'s May 2016 issue, I wrote "Hot results from a cool planet," detailing many of the initial findings we made as the Pluto system data began raining down from the Kuiper Belt. Here, I will supplement those early findings with four

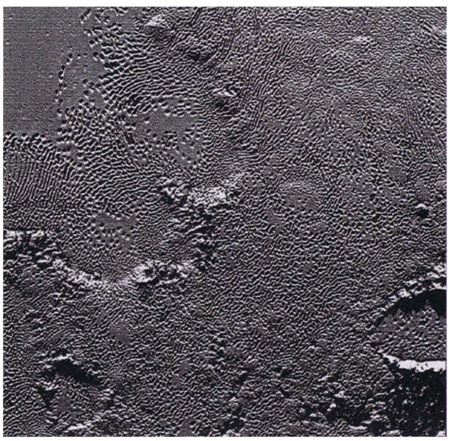
PUZZLED BY PLUTO





Above: The nitrogen ice glacier Sputnik Planitia covers some 400,000 square miles (1 million square kilometers) of Pluto's surface. It is the largest glacier known beyond Earth and appears devoid of craters, implying that some process continuously renews it. (All feature names in this story are informal.)

Right: The cellular patterns seen in western Sputnik Planitia suggest that convective motions within the ice constantly renew the surface by replacing older ice with fresher material from below.



Hundreds of sublimation pits dot the "coastline" of Sputnik Planitia. Scientists think these pits form when nitrogen ice turns directly into gas. New Horizons captured this high-resolution view just 13 minutes before closest approach.

overarching results that stand out from the first exploration of Pluto.

Unique landforms

One of the biggest surprises in the imagery that New Horizons returned is the many new kinds of landforms seen on Pluto's surface. Yes, Pluto displays heavily cratered terrains, polar deposits, canyons, glacial channels, mountain ranges, and even chaotic mountain blocks like those seen on Mars and on Jupiter's moon Europa, and we didn't expect to see so many of these landform types. But even more surprising are the exotic new types of landforms on Pluto.

The star of this show is the vast, 400,000-square-mile (1 million square kilometers) nitrogen glacier informally called Sputnik Planitia (SP), which forms the western lobe of Pluto's "heart." No nitrogen glacier has been seen elsewhere in the solar system, and no glacier of this extent has been seen anywhere beyond Earth.

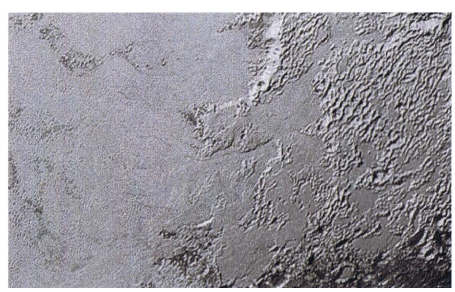
Several features within SP enhance its exotic nature, including cellular structures on its surface (which indicate convective motions in the ice), recharge zones found along its edge, hundreds of mile-wide sublimation pits formed where nitrogen ice has turned directly into a gas, and clear evidence of glacial flow against the surrounding mountains near the northwestern shoreline. Also surprising is the complete lack of craters on SP, indicating that this gargantuan feature renews itself continuously despite a temperature of just 40 kelvins (72° F above absolute zero)! More on that later.

Another completely unique landform on Pluto is the widespread "bladed terrains" of the region informally called Tartarus Dorsa. These long, 1,000-foot-high (300 meters) linear ridges made of methane ice are unlike anything seen elsewhere in our solar system. Moreover, the bladed terrains appear to extend far beyond Tartarus Dorsa and cover wide expanses of the low latitudes on the far-side hemisphere that we imaged only at low resolution. The bladed terrains may even be one of the dominant landform types on Pluto. What causes this terrain? Some scientists suggest that these structures may be penitentes — blades of ice that form in high deserts under sunlight-driven sublimation. Others suggest that they may be the result of wind sculpting or glaciation. There are several ideas, but no clear favorite yet.

New Horizons also discovered unique terrain types on Charon. Although this moon has much the same size, density, and surface composition as some of the mid-sized icy satellites of the giant planets, it shows two types of surface features not seen elsewhere. One is the dark, red polar stain I mentioned earlier. The best theory is that it formed when gases escaped from Pluto, condensed onto Charon's cold poles, and then were chemically altered by solar radiation. Charon's other unique feature is a handful of "moated mountains," each surrounded by a quasi-circular trench. The cause of these structures remains a mystery.

Clinching the giant impact

It has been more than 30 years since planetary scientists like Bill McKinnon first suggested the Pluto-Charon binary formed in a giant impact. In this scenario, a collision between Pluto and another small planet



Nitrogen ice flows from the highland region on the right side of this image onto the frozen plains of Sputnik Planitia through narrow valleys just 2 to 5 miles (3 to 8km) wide.

New Horizons helped clinch the case that Pluto's satellite system formed as a result of a giant collision between a rogue Kuiper Belt object and the young Pluto. Debris from the impact formed a disk around the battered Pluto that eventually coalesced into Charon and its cohort of four much smaller moons.
RON MILLER FOR *ASTRONOMY*

launched material into orbit around Pluto that then accumulated to form Charon.

Early clues supporting this formation hypothesis included the large mass of Charon relative to Pluto and the off-the-charts specific angular momentum (the angular momentum per mass) of the binary. Further evidence arrived in the 1990s with the discovery of the Kuiper Belt, which provided a source population for the necessary impactors, and the Hubble Space Telescope's discovery of Pluto's four small moons all in the same orbital plane as Charon.

New Horizons data add to the case for a giant impact origin in three significant ways. First, the spacecraft revealed the compositions of Nix and Hydra for the first time, showing they are covered in water ice. This is exactly what numerical simulations had predicted a giant impact would produce. Second, New Horizons images more precisely determined Charon's volume and thus refined this large moon's density. The improved density measurement indicates Charon is more icy and thus less rocky than Pluto, which is just what you would expect from a giant impact on a Pluto differentiated into a core, mantle, and crust.

Scientists have seen nothing like the so-called bladed terrains of Pluto's Tartarus Dorsa region elsewhere in the solar system. These ridges rise some 1,000 feet (300 meters) above their surroundings in this enhanced color view.

Finally, New Horizons imaged Nix and Hydra in sufficient detail to allow scientists to count craters on their surfaces and thus estimate their ages. (A surface accumulates more craters over time.) This let us compare the surface ages of Nix and Hydra to the age of Charon, similarly derived from New Horizons images. When our science team completed these studies last year, we found that all of these objects are equally old — providing yet another link to their common origin. Together, these latest clues make it all but impossible to imagine any other formation scenario for the Pluto system than a giant impact.

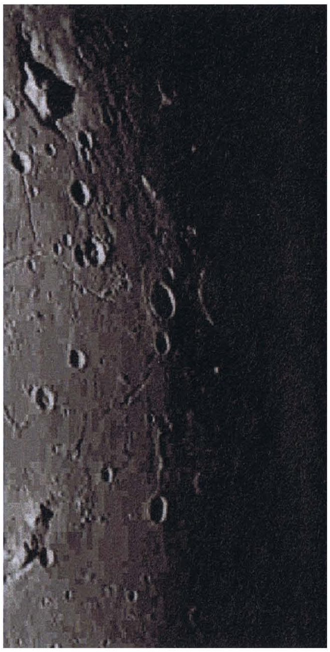
Time-variable Pluto

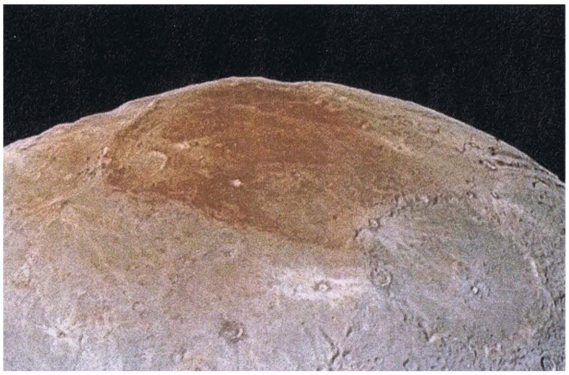
Another big surprise we found on Pluto is widespread evidence for temporal changes

Pluto's small moons, including Nix (pictured) and Hydra, bolster the case that a giant impact created the entire satellite system. New Horizons showed that water ice covers both moons, and both are the same age as the large moon, Charon — exactly what you would expect from a giant impact origin.

on its surface. This evidence comes in several forms.

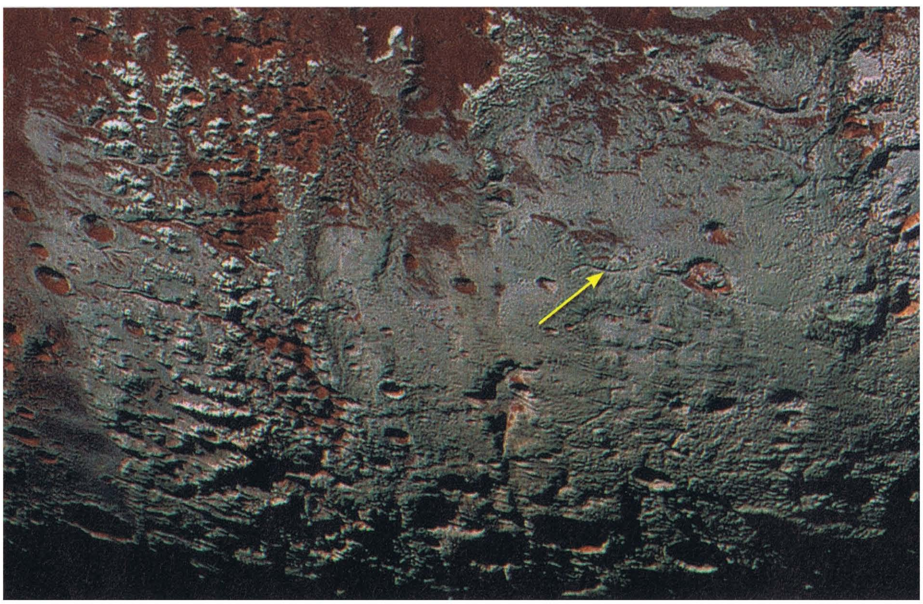
SP provides some of the best examples. As I noted earlier, it has no detectable craters on its surface and cannot be older than perhaps 10 to 30 million years. This means it either was created recently or, more likely, continuously renews itself. The cellular patterns of ice convection may be an indication





Above: Pluto's large moon, Charon, also possesses some unique landforms. The dark, red stain that covers the satellite's north polar region appears to be material that originated in Pluto's atmosphere and then condensed on Charon's cold polar terrains. Exposure to solar radiation then darkened and reddened the material.

Left: Charon's other unique landforms are several "moated mountains" like the one seen at the top left. In these features, a quasi-circular trench some 0.6 to 2 miles (1 to 3km) deep surrounds the mountain.



Valley networks that appear to have been cut by flowing liquids or ices provide some of Pluto's best evidence for temporal changes. The one here (arrow) lies south of the equatorial band Cthulhu Regio.

of this renewal process. But the evidence for temporal change on SP goes well beyond that. In fact, we see signs for both glacial recharge in the form of recent flows down the slopes of the surrounding mountains and for currents in SP's nitrogen ice. The currents themselves are a form of temporal change as the ice moves and possibly slides under some of the mountains that SP abuts.

More evidence for temporal change appears on the flanks of the feature informally called Wright Mons. Wright Mons is a caldera-like structure that likely formed by cryovolcanism — the eruption of water or other volatile liquid. And Wright Mons is huge, rivaling Hawaii's Mauna Loa in scale. But strikingly, its flanks show essentially no evidence of cratering, which implies that either the mountain itself is young or it has been active recently, resurfacing the flanks.

Although the signs of large-scale temporal changes in SP and on Wright Mons are impressive, in my book, the most interesting evidence for such changes on Pluto is something else entirely. Across the surface, we see geological features that strongly resemble sloping valleys and dendritic valley networks on Earth and Mars. On those other two planets, flowing liquids or ices create such structures via erosion. We also see one surface feature, informally called Alcyonia Lacus, that appears to be a frozen lake nestled in a low-lying part of the chaotic mountain blocks that make up the informally named al-Idrisi Mountains. This 19-mile-long (30km) feature is replete with a smooth surface and distinct shorelines.

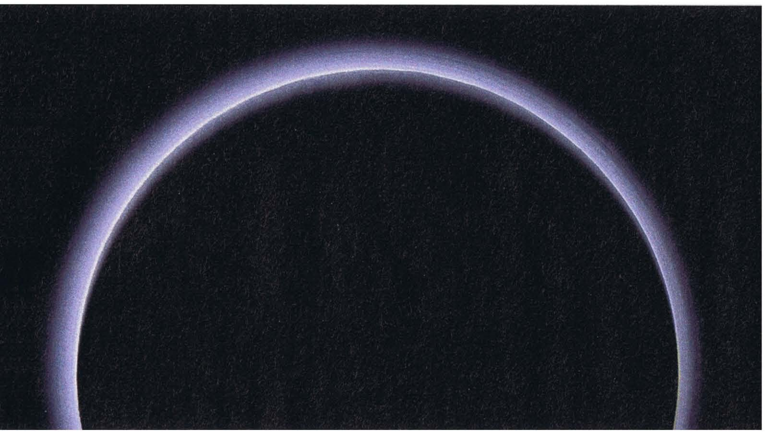
Perhaps the strangest aspect about the possibility that liquids once existed on Pluto's surface is that both the temperature and surface pressure today are far too low to allow liquids. In fact, for liquids to exist on Pluto's surface, temperatures and pressures must exceed the triple point — the conditions under which the solid, liquid, and gas phases of a substance can coexist in equilibrium — of molecular nitrogen, carbon monoxide, or methane. But this in turn requires atmospheric pressures exceeding 100 millibars — about 10,000 times Pluto's current surface pressure of 11 microbars. How can this be?

Scientists discovered in the 1990s that the tilt of Pluto's axis varies by more than 20° every 3 million years. A similar process on Earth, called Milankovitch cycles, causes our own polar tilt to change, but by about 10 times less. Still, even that small shift creates significant climate variations on Earth. In a recent paper in *Icarus* on which I was lead author, we modeled the kind of atmospheric pressure and temperature variations that Pluto's much larger polar tilt variations may cause. We found it is plausible that such cycles caused conditions on Pluto to sometimes exceed the pressures and temperatures of the nitrogen triple point. If further modeling bears us out, this would allow liquids to be stable and even flow on Pluto's surface thousands of times in the past!

Ocean worlds?

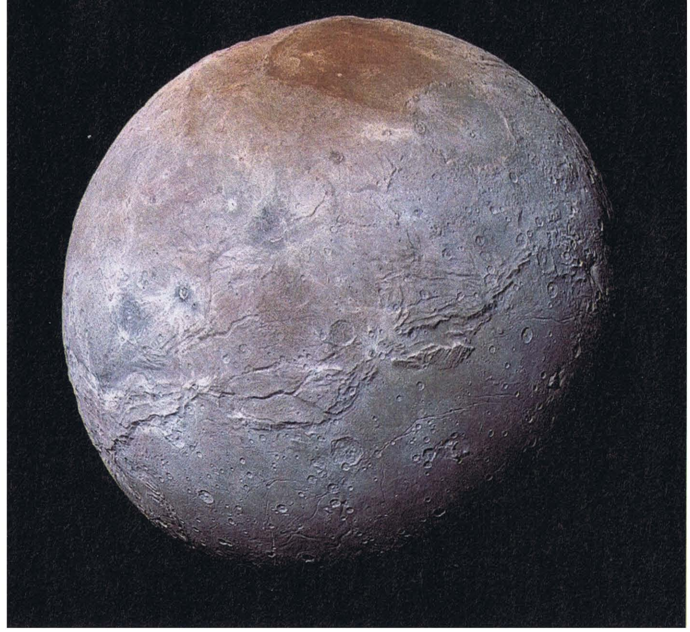
At the dawn of the Space Age, Earth was the only known world to have an ocean. Later, increasingly detailed studies of Mars by spacecraft revealed that it almost certainly once had vast seas or oceans of water that have long since disappeared. But to our great surprise, spacecraft also found that many worlds with icy surfaces — including Enceladus, Europa, Ganymede, and Titan — show evidence for internal oceans.

Why should this be so? First, water ice is common to the surfaces and interiors of virtually every solid world in the middle and outer solar system. Second, pressures and temperatures increase with depth, meaning that the water ice often reaches a liquid state in the interiors of these worlds. This typically occurs tens to hundreds of miles below the surface, creating the conditions for global interior oceans with depths



Above: New Horizons found lots of evidence that liquids once existed on Pluto's surface. For this to be so, the atmosphere — seen here as a bluish arc in one of the spacecraft's parting shots — must have been much warmer and denser in the past.

Right: Alcyonia Lacus lies in the mountains just north of Sputnik Planitia. The feature appears to be a frozen, former lake of liquid nitrogen.



The huge tectonic belt that runs along Charon's equator provides dramatic evidence that this moon's interior once held a large water ocean. Scientists think the belt formed from stresses when the water froze and expanded.

and volumes that are, in some cases, even larger than Earth's.

Evidence for these oceans was once only theoretical, coming from computer calculations of interior conditions. But later we found water geysers erupting from the interiors of Enceladus and Europa, and magnetic field variations that suggest electrical currents in salty interior oceans in three of Jupiter's Galilean satellites.

A few years ago, geophysical models indicated that Pluto and Charon might be able to host interior water oceans, or at least to have done so in the past. But when New Horizons arrived, it revealed new evidence that such oceans are actually likely.

The 90-mile-wide (150km) Wright Mons (shown at lower left) appears to be a shield volcano complete with a deep central pit at its summit. The mountain's flanks show no evidence of impact craters, suggesting that it either is young or has recently erupted.

In the case of Charon, a primary sign for an ancient interior ocean is the giant extensional tectonic belt that girdles the moon's equator. Our team suspects the belt originated from stresses created long ago when liquid water in Charon's interior cooled, expanded, and froze after the satellite's violent formation in a giant impact.

The case for an ocean inside Pluto is more nuanced. SP suspiciously lies diametrically opposite to Charon. (Pluto and Charon are tidally locked and thus keep the same faces toward each other.) The odds of this occurring randomly are small. But if there is an interior water ocean that wells up under SP, it would create an excess of mass there because water is denser than water ice. Tidal forces would then naturally reorient SP to just the location we see it — opposite Charon. Of course, this evidence is only circumstantial. If we return someday with an orbiter that can map gravity anomalies, search for magnetic variations, and perhaps even carry a surface-penetrating radar, we can definitively test for this ocean.

The value of exploration

Clyde Tombaugh discovered Pluto 85 years before New Horizons flew past it. During those 85 years, the distant world never appeared as more than a smudgy disk in images. Yes, from afar we learned its basic surface composition, that it has a nitrogen-dominated atmosphere, and that it forms a binary planet with Charon. Yes, from afar we learned Pluto's rotation period and polar tilt, and that it has four small moons. And yes, from afar we learned that the surface is reddish with brighter and darker areas, and that Pluto's interior is made primarily of rock.

But frankly, despite the vast advances in observing capabilities from 1930 to 2015, there wasn't much more we learned about the Pluto system from Earth or Earth orbit. I doubt that if I lived to be 120, we could have learned as much in all those years as we found out in a matter of days while New Horizons zipped by. The lesson of New Horizons is that it took a mission of close-up exploration to really determine Pluto's basic nature.

And so, while I am sure that new tools like the James Webb Space Telescope and the planned 30-meter-class telescopes on the ground will add some detail, I doubt that we will learn much more until we follow up New Horizons with an orbiter or orbiter-lander pair. I also doubt that we'll ever know as much about the other small planets of the Kuiper Belt as we now know about Pluto unless we send probes to fly by them as well. New Horizons re-emphasized the lesson that all those first missions to explore the closer planets in the 1960s, 1970s, and 1980s taught a previous generation of scientists and scientific enthusiasts: There is no substitute for spacecraft exploration.

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