Research News

Triton Steals Voyager's Last Show

Even after 7 billion miles of exploration, Voyager 2 observations of Neptune, its rings, and its moons can still stir controversy about the giant outer planets

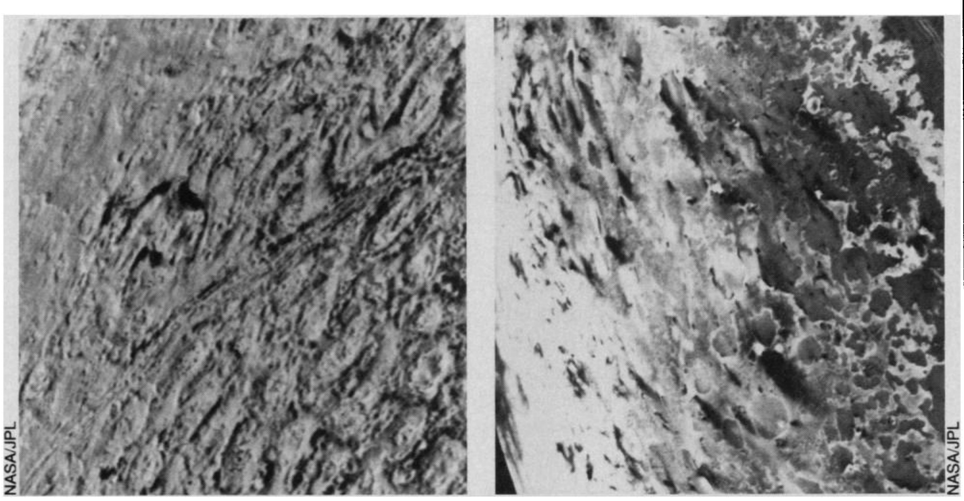
Jet Propulsion Laboratory, Pasadena

IT HAD BEEN A LONG, productive trip. Until last week, the Voyager 2 spacecraft had visited three gas-giant planets, a dozen major moons, a score of smaller chunks of ice and rock, and three ring systems with literally thousands of rings composed of myriad tiny moonlets. It had returned five trillion bits of data, including over 100,000 pictures of the exotica of the outer solar system—the so-called pizza that is Jupiter's orange moon Io spouting jets of sulfur from its volcanoes; hamburger-shaped Hyperion tumbling chaotically in its orbit around Saturn; the geologic hodgepodge of Uranus' Miranda, an orb that looks more like a stack of flapjacks than a moon. And yet there would be more: Voyager's last encounter in this solar system was to be a spectacular final act in its 12-year drama.

In the aftermath of Voyager's dash by Neptune last week, Voyager scientists are hip deep in heavenly data about yet another surprising planetary system. Neptune itself was notable for the inexplicable perversity of its winds (see box, p. 929), its Earth-like cirrus clouds, and the string of unique clumps on one of its rings that researchers dubbed sausages (see p. 930). But the star of the show was the pink-tinged cantaloupe that is Triton, Neptune's largest moon. "Even though Voyager has explored dozens of bodies through the solar system," said Edward Stone of the California Institute of Technology and the Voyager project scientist, "there was nothing like Triton."

Well, certainly no single body in the solar system. Seven hours after Voyager began sending back close-ups of Triton in the wee hours of the morning, imaging team co-leader Lawrence Soderblom of the U.S. Geological Survey in Flagstaff was struggling to explain what it all might mean by combining bits and pieces of other solar system bodies—icy slush had oozed out of fractures much as had happened on Uranus' moon Ariel, ice lava formed frozen lakes as on Jupiter's Ganymede, and polygonal patterns were reminiscent of the remnants of Mars' retreating polar ice cap. But then there were the cantaloupe skin of close-packed dimples and the dark spots ringed by white bands. How do you explain those?

Indeed, Triton's uniqueness led to scientific controversy almost as quickly as the images arrived on the space scientists' monitors. As the early pictures came down, discussion centered on the large-scale volcanic processes that shaped and reshaped Triton's surface. The question was whether the surface Voyager showed us last week was formed billions of years ago or whether it was altered more recently. Either way, no one gave much thought to the possibility that anything was going on today. But all that changed as researchers perused higher resolution shots a few days later. Suddenly, a different, more limited, sort of volcanic activity, which may still be taking place, became the focus of speculation.



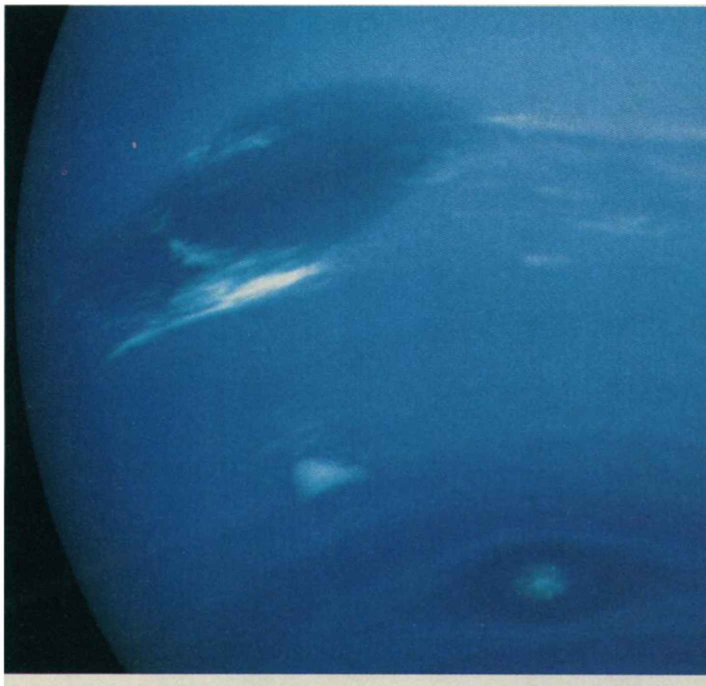
Enigmatic geology. *Close-up of Triton's surface (left) shows circular depressions and rugged ridges. South polar region (right) shows dark streaks, possibly caused by nitrogen eruptions that may still be taking place.*

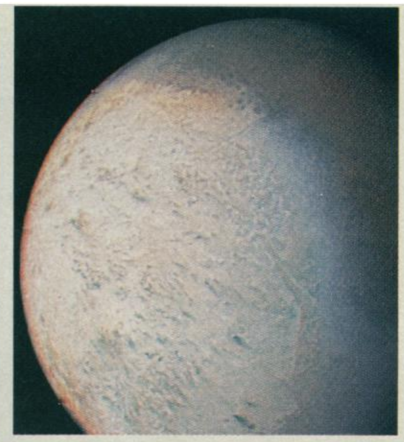
But first, the controversy over the ancient, large-scale processes. Stepping out on a limb shortly after Voyager's closest encounter with Triton was photogeologist Soderblom. He told a packed press conference, "I would guess [the age of the volcanic activity] is measured in millions or tens of millions [of] years." After more than 4 billion years of existence, that would make Triton one of the most spritely of the solar system's moons. Two days later, Soderblom revised his theory, but differences of opinion over his initial speculation provided a public example of the conflicts that help drive scientists toward new understandings.

An early dissenter was planetary physicist David Stevenson. "I don't really buy geologically recent volcanism," he told *Science* after watching the same images of Triton march across a Voyager monitor at Caltech. "I don't see any need for volcanism less than about 4 billion years ago."

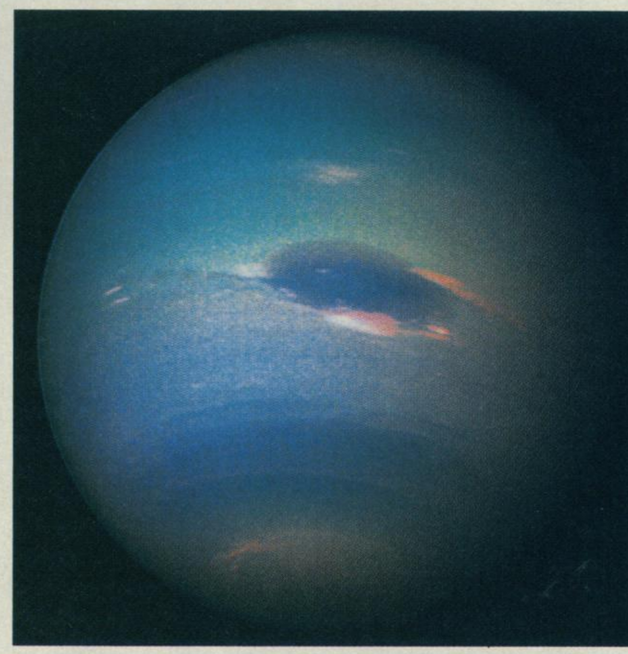
According to everything Stevenson knows about the way moons work, Triton should be stone-cold dead. It takes energy to drive erupting geysers or even slush flowing onto the surface. But Triton should have precious little heat energy to draw on. Neptune's gravity is not kneading Triton like so much clay, the way Jupiter squeezes Io to generate the frictional heat that drives that moon's globe-girdling volcano system. And Triton also has a dearth of the radioactive decay heat that drives Earth's volcanoes and drifting continents. Triton's inner fires are long damped, and internally driven modification of its surface faded along with them, argued Stevenson.

But despite their differences, planetary scientists do agree that Triton was not always gripped by a frigid inertness. Judging by Triton's orbit, it should have had all the energy it needed in its early days to reshape itself. Dynamicists have long been struck by Triton's odd orbit about Neptune—unlike any other known moon, the 2700-kilometer





False-color image of Neptune (below) shows details of the cloud structures. Triton (near left) viewed through green, violet, and ultraviolet filters. Narrow-angle view of Neptune (far left) shows the Great Dark Spot with a bright feature to the south and a second dark spot still further to the south. [NASA/JPL photos]



Another weather report from the outer planets. Voyager 2 has provided the fourth and final example of what the weather can be like on a huge ball of gas. So far on Neptune, it is far from dull. Notes meteorologist Andrew Ingersoll of the Voyager imaging team and Caltech, "It's a mistake to think of the meteorology of the gas giants as the same problem repeated four times. It teaches me a certain humility. All the great knowledge we have of the Earth does not generalize very well. Uranus doesn't even generalize to Neptune."

The behavior of the storms of Neptune illustrates some of Ingersoll's lessons in humility. Voyager detected the Great Dark Spot in January (at the top of the picture above). Its strong resemblance to Jupiter's swirling Great Red Spot and the eventual detection of three other cloud systems encouraged comparisons with Jupiter, the solar system's premier weathermaker.

Fat chance. During the weeks before the encounter, no new features appeared that would mark the winds and so help clock their speed. To make matters worse, some clouds are very high in the atmosphere (as highlighted by Voyager's false-color image, right) and do not move with the wind. Instead, they cling to the spot the way clouds can hug a mountaintop in a high wind.

Despite the frustrations, imaging team members developed a rough sketch of Neptune's winds—they seem to be mostly backwards, blowing westward at mid- and low latitudes relative to the planet's interior. "It's just the flip of Jupiter and Saturn," says Ingersoll. The four examples now in hand have made clear that "it's the rotation of the planet that organizes the wind pattern." ■ **R.A.K.**

body moves opposite to the direction that the planet rotates and in an orbit inclined 21° to Neptune's equator. Such ill-behaved motions have been taken as signs that Triton did not form in orbit around Neptune. Instead, it is an intruder, an outsider captured as it was passing by. After capture, Triton would have gone into a highly elliptical orbit.

The most detailed prediction of what happened next came from Peter Goldreich, a colleague of Stevenson's at Caltech. As Triton's orbit took it alternately close to Neptune and far away from the planet, it would have been subjected to the same kind of gravitational kneading that now drives Io's volcanoes. The Caltech group calculated that this would have kept Triton almost entirely molten for much of its first billion years as a satellite of Neptune. That would have meant plenty of volcanism, at least for a while. But after a few hundred million years, Triton's orbit would have rounded out, causing Triton to chill rapidly. This would have ended large-scale volcanic activity, as Stevenson was arguing.

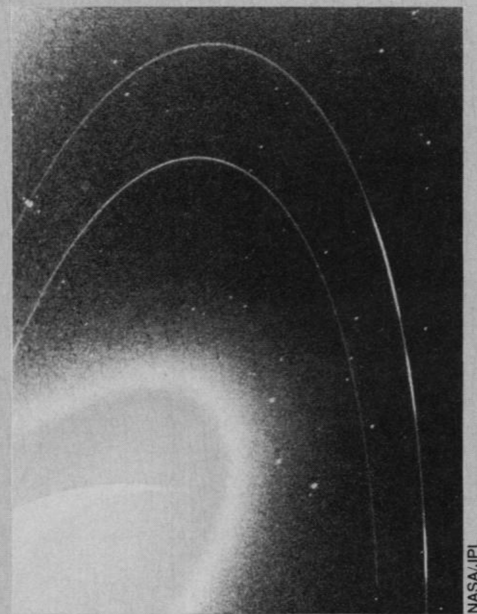
Triton, as revealed by Voyager, looks like it was indeed largely molten long after the earliest days of the solar system. Images showed no planet-scale blemishes left from 4 billion years ago, when swarms of planetesimals struck all solar system bodies. Triton's near molten state, as predicted by the Caltech group, would have erased all the craters left by this heavy bombardment. Goldreich and his colleagues also predicted that as Triton swung through its eccentric orbit, it would have smashed and swept up any of Neptune's original moons orbiting more than about 125,000 kilometers from the planet. Voyager discovered six new moons; all are within 115,000 kilometers.

With these signs suggesting that volcanic activity driven by internal heat ended early, Stevenson looked for other explanations for features such as lava lakes that appear to have been formed more recently. Those, he said, might be accumulations of frozen

Why Neptunian Ring Sausages?

While Triton's geological history was being debated, another conflict between hard-core theorists and more observationally oriented researchers was simmering, this time over Neptune's rings. Before Voyager's arrival, all that ring specialists could find around Neptune were ring fragments, a few short arcs detected when they happened to dim the light of a star passing near the planet.

Theorists latched on to ring arcs right away. The problem was that an arc, left to itself, would spread around its own orbit to form a complete ring within a few decades. What keeps an arc an arc? Among proposed theories, Peter Goldreich of Caltech, Scott Tremaine of the University of Toronto, and Nicole Borderies of the Jet Propulsion Laboratory suggested that a single satellite at least 200 kilometers across in an inclined orbit could ride herd on dozens of arcs through the subtle gravitational nudges given by such a satellite. All they had to do was find the satellite.



Ring arcs, strung together.

As it turned out, Voyager found everything but the postulated satellite. On the way in toward the planet, Voyager imaged three arc segments and strung them together on a faint but complete ring—one too faint for Earth-based observers. The spacecraft also imaged a second, fainter ring interior to the arc-laden, sausage-string ring. Looking back on its way past the planet, Voyager detected a third, even fainter, ring between the first two, as well as two broad dust bands. Of its six satellite discoveries, one has an inclined orbit, but it is only 50 kilometers in diameter.

"It's a long shot because it's so small," Goldreich told *Science*, "but this inclined satellite is our only shot." Another moon discovered by Voyager might account for the sausage effect, but that still leaves the question of why the string of sausage is all in one 35-degree sector of the ring. "What we've been doing the past week has been racking our brains for a mechanism," said Tremaine. "At the moment we're stuck. Maybe we're just missing something." The inclined satellite's orbital distance is a tantalizing 1% from where their mechanism would work, given a large enough satellite, but they could not tell until the imaging team, which was undoubtedly thinking along the same lines, released a precise orbit. At one of the last press conferences, however, Carolyn Porco of the imaging team shattered their faint hopes. The new satellite cannot form the arcs.

While the Goldreich group was huddling at Caltech, looking for a neat, elegant theory or two, Larry Esposito of the University of Colorado was thinking about how messy rings are looking. "This clumpy ring reminds me of the F ring at Saturn," Esposito said in an interview the day after the encounter. The F ring was a frenetic ring with kinks, snaking strands, and clumps. Current thinking attributes its bizarre behavior to the gravitational effects of small satellites—both those that shepherd the ring particles on either side and moonlets embedded within the ring itself—as well as collisions among moonlets that shake loose debris to form clumps.

"I think these mechanisms proposed for the F ring can explain what we see at Neptune," said Esposito. "Rings are not a geological monument held together by old, strong forces," he said, referring to the Goldreich group's approach. "They are piles of debris."

Those piles come and go, shift and reshape themselves, as chance intervenes with random collisions and sideswipes by shepherd satellites. "I've thought for years that the rings are more stochastic. The Voyager data have brought home to us the random nature of rings," said Esposito. ■ R.A.K.

methane and nitrogen that fell out of Triton's thin atmosphere, the equivalent of Earth's snow. A layer of Triton ice could even flow like a glacier, he suggested.

But there are always caveats in such instant science. "Everything I say is as hasty as what Larry [Soderblom] said," Stevenson noted, "so I may change my mind."

But it was Soderblom who changed his mind. With more time to ponder Triton images, especially late-arriving high-resolution pictures, Soderblom was finding so many craters formed by the drizzle of meteorites since the heavy bombardment that it was clear nothing had erased features on the surface of Triton for a long time. "The crater populations are consistent with Triton being active for a couple billion years and then quiet for the last couple billion," he said.

With that conclusion, Soderblom promptly launched into instant science again. This time, he suggested that nitrogen-driven volcanoes are active today and may explain dark streaks that everyone—scientists and press alike—was already speculating about. Such limited volcanic activity, as opposed to the planet-wide landscaping of the past, might need only the slightest trickle of heat from the interior, he said.

"This is a crazy idea, it is probably wrong," Soderblom said, "but it's the best we have. We're thinking in real time."

But when science is done in a hot glare of publicity, preliminary ideas end up in every newspaper in the country. Crazy ideas can then become embarrassing, but such was not Soderblom's fate. To the contrary, Stevenson finds Soderblom's latest idea far more appealing than his earlier musings. "My mind was changing as I watched the latest Triton images come in," he said. The more detailed views suggested some younger activity to him too. They were so suggestive that he started drawing nitrogen geyser diagrams long before he heard Soderblom's press conference.

But what is driving this limited activity? "Internal heat is a long shot," says Stevenson. He prefers a sun-driven cycle, not unlike Earth's hydrological cycle of evaporation and precipitation, that separates nitrogen from methane, moves the nitrogen from place to place, and interacts with the seasonal cycle. Remixing of nitrogen and methane might then provide an energy source.

As Voyager speeds out of the solar system it is leaving behind a lot of puzzles like Triton's enigmatic geology. It is also leaving one unanswerable question: What is Pluto like? ■ RICHARD A. KERR