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Neptune portfolio: spectacular visit to a turbulent planet.

Double-beta decay: observing the undetectable.

Yellowstone: the fires are out, the debate burns on.

Shuttle glow: *250 kilometers above the earth an attenuated wind raises a halo of light from the spacecraft's skin.*

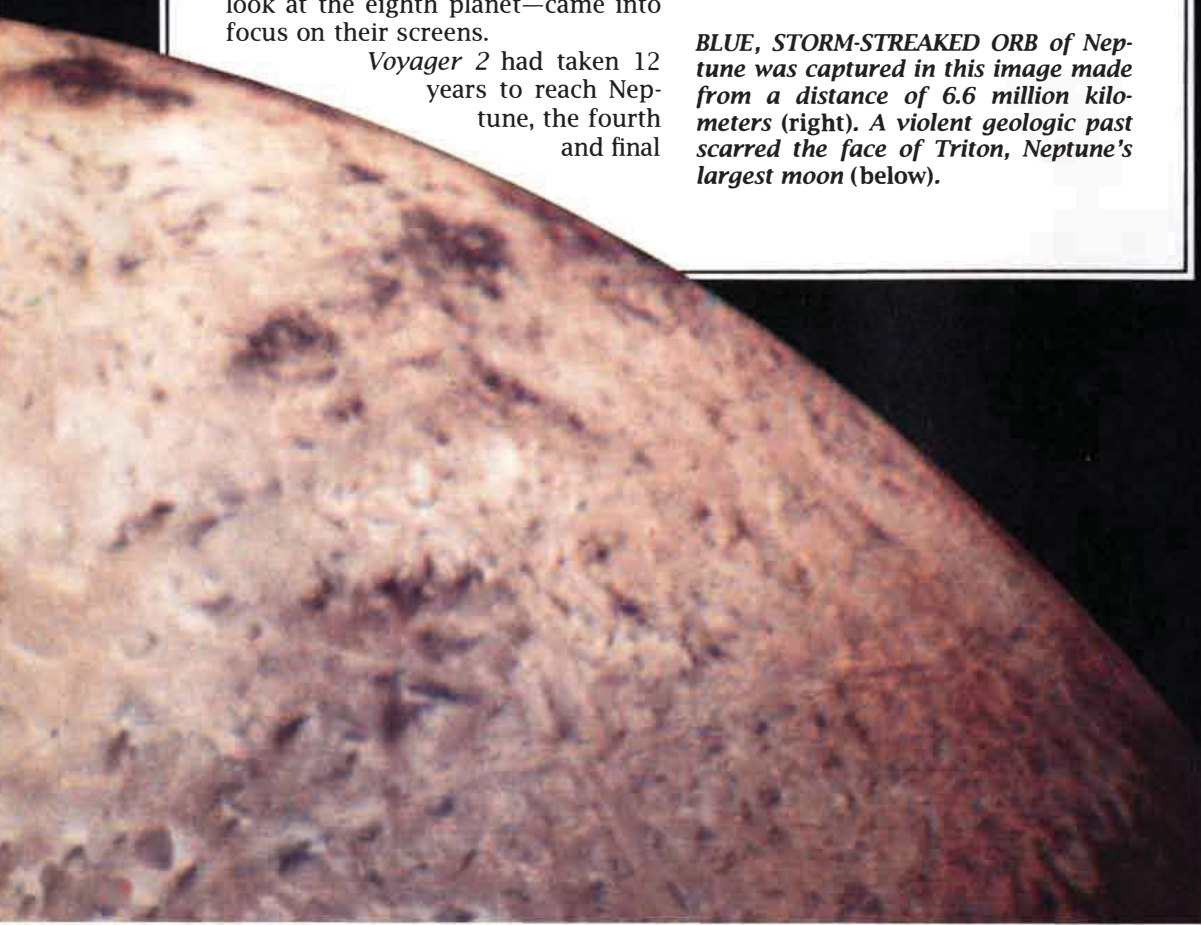
Neptune

Voyager 2's cameras unveil a stormy world and a frozen moon molded by volcanism

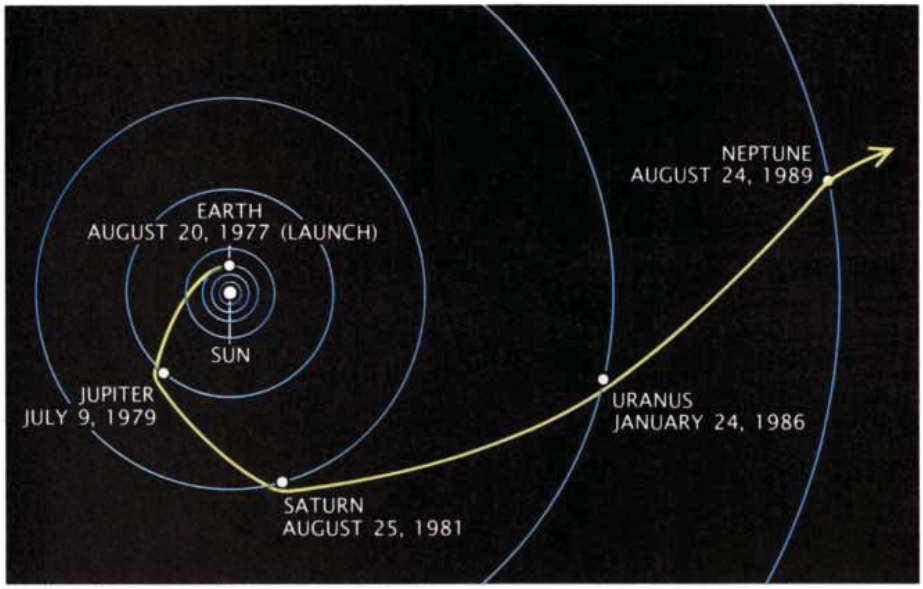
by June Kinoshita

On the night of August 24, a small, angular contraption hurtled over the cloud tops of Neptune. It swooped barely 3,000 miles above the great blue planet's north pole, plunged down the night side, scooted past the large moon Triton at a distance of 24,000 miles and vanished into the void. During that brief encounter the visitor meticulously snapped thousands of images and radioed them to the earth. Scientists waiting at the Jet Propulsion Laboratory in Pasadena, Calif., cheered and uncorked the champagne as the pictures—humankind's first close-up look at the eighth planet—came into focus on their screens.

Voyager 2 had taken 12 years to reach Neptune, the fourth and final destination of a planetary pilgrimage that included Jupiter and Saturn (both were also visited by the probe's twin, *Voyager 1*), as well as Uranus. Of all the planets on the itinerary, Neptune was the least known. Overhauling the on-board computer programs and gingerly firing the thruster rockets, the Voyager team steered the aging ship to a flawless encounter. From signals that reached the earth with a strength of less than a ten-quadrillionth of a watt, the team gleaned images of breathtaking clarity. On these pages *Scientific American* presents the last fruits of the epic journey.



BLUE, STORM-STREAKED ORB of Neptune was captured in this image made from a distance of 6.6 million kilometers **(right).** ***A violent geologic past scarred the face of Triton, Neptune's largest moon*** **(below).**



***VOYAGER'S GRAND TOUR** of the outer planets took advantage of a once-in-a-176-year planetary arrangement that enabled the spacecraft to be catapulted from one planet to the next by gravity. Originally designed to probe only Jupiter and Saturn,* Voyager 2 *was remotely reprogrammed to operate at Uranus and then Neptune, currently the most distant planet in the solar system. (Pluto's eccentric orbit has for the moment taken it inside Neptune's orbit.) The spacecraft dove over the north pole of Neptune, sped past Triton and headed south out of the solar system.*

***METHANE GAS** in Neptune's atmosphere is mapped in this false-color image made with a filter that admits light at a wavelength absorbed by methane gas. Haze high above the methane layer reflects sunlight at the edge of the disk, resulting in a bright red rim. At the center of the disk, sunlight penetrates the haze and is absorbed by the methane, giving rise to a blue color. Highly reflective cirrus clouds appear as bright patches of white.*

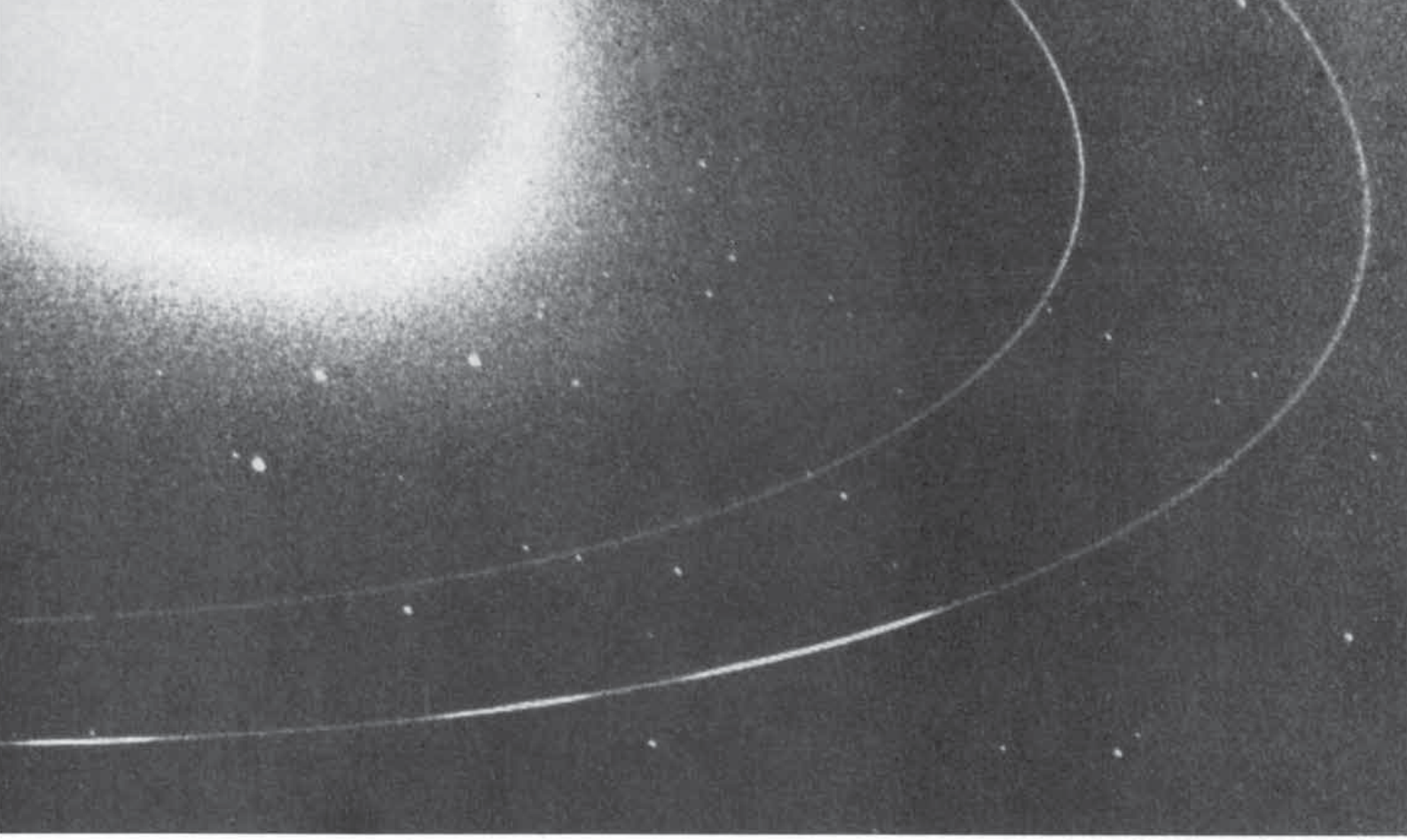
Orbiting at a distance of 4.5 billion kilometers from the sun, where the light is a thousandth as strong as it is at the earth, Neptune barely shows up as a pale-green speck in the most powerful earthbound telescopes. Indeed, the planet was found only 143 years ago, after astronomers speculated that the gravitational pull of an eighth planet accounted for anomalies in the orbit of Uranus. Since then, observers have estimated Neptune's mass, size and composition, all of which suggested that it would be much like its bland "twin," Uranus. To their surprise, *Voyager 2* revealed a turbulent world, with giant storm systems rivaling those of Jupiter and fleeting clouds unlike any seen before on a gaseous planet.

Like Uranus, Neptune is a great ball of water and molten rock cloaked in an atmosphere of hydrogen and helium mixed with methane. The methane absorbs red light and is responsible for the planet's aqua hue. Unlike Uranus, Neptune's atmosphere bears distinctive striations and gigantic dark storm spots, including one hurricane as wide across as the earth, which scientists quickly christened the Great Dark Spot. First detected by *Voyager 2* this past winter, the massive storm is located at about 22 degrees south latitude and appears to churn in a counterclockwise direction. Later, the cameras picked up a smaller dark spot farther south. *Voyager* images also showed a small bright cloud, named Scooter, dashing along at an intermediate latitude between the two spots.

Radio signals, which issue from the planet like a beam from a lighthouse, disclosed that Neptune completes one rotation in 16 hours and three minutes—about one hour faster than had been predicted. Images made over several complete rotations revealed that the small dark spot travels at about the same rotational period and so remains in roughly the same position with respect to the planet. The Great Dark Spot takes longer, about 18 hours, to complete a rotation and so must be sweeping westward against the planet's rotation at a speed of 300 meters per second, or 700 miles per hour, driven by the fastest retrograde winds *Voyager 2* has ever clocked.

Two hours before *Voyager 2*'s closest approach to the planet, the spacecraft's cameras happened on a startling and beautiful sight: catching the oblique rays of the sun, parallel banks of silvery cirrus clouds were casting shadows on the blue cloud deck below. From the po-

SILVERY CIRRUS CLOUDS in Neptune's northern hemisphere cast shadows onto the blue cloud deck 50 kilometers below. The clouds extend over thousands of kilometers. Two images taken 17.6 hours apart from a distance of 12 million kilometers document the atmosphere's dynamism (inset). *The planet completed a little more than one full revolution in the interim; the small dark spot rotated at the same speed as the planet, but the Great Dark Spot swept westward at a speed of 1,000 kilometers per hour.*



"LOST ARCS" turned out to be bright clumps in Neptune's outer ring, seen here from a distance of 1.1 million kilometers as* Voyager 2 *left the planet.

sition of the shadows and the angle of the sun, members of the imaging team estimated that the clouds hovered some 50 kilometers above the underlying layer. Scientists were ecstatic: such three-dimensional structures had never before been observed in the atmosphere of any other giant planet.

The delicate wisps testified, paradoxically, to a dynamic atmosphere. According to Robert West of the photopolarimetry team, the stratification indicated that Neptune is more dynamic than even Jupiter, which, apart from its roiling red spot, has a flat if colorful cloud layer. Scientists cannot yet explain how the high clouds form or why they extend along only a few lines of latitude.

High cirrus clouds also draped the south rim of the Great Dark Spot and formed a bright dimple above the center of the small dark spot. The cloud formations remained in more or less the same location, even though they were surrounded by violent winds. Bradford A. Smith, head of the imaging team, speculated that updrafts loft gaseous methane high into the atmosphere, where it freezes into icy cloud particles; downdrafts then drag the clouds down to warmer regions where they dissipate. A similar process creates cloud formations above terrestrial mountains.

Neptune's magnetic field held surprises: its dipole axis is tilted some 50 degrees from the rotation axis and is also displaced from the planet's center by 10,000 kilometers. The finding helped to clarify a problem that had puzzled planetary scientists ever since *Voyager 2* disclosed that Uranus's magnetic-field axis was similarly tilted. Because the magnetic fields of other planets tend to coincide with their rotation axes, scientists had speculated that the tilt might be related to the unique orientation of Uranus's rotation axis, which lies in the plane of its orbit. Another possibility was that, by sheer chance, *Voyager 2* had caught the planet in the middle of a reversal in the direction of its magnetic field.

But with the new finding about Neptune's magnetic field, neither explanation is plausible anymore. Neptune's rotation axis has the usual more nearly perpendicular orientation, and the chances of catching two planets in the midst of magnetic reversals are slim. On the other hand, according to Norman F. Ness, head of the magnetic-field experiment, skewed magnetic fields are common to a class of stars called oblique rotators. He suggested the planets' fields could arise by the same mechanism that has been proposed for the stars: the convection of electrically conducting material within a thin, spherical shell near the surface. (On the earth the convection occurs within a molten metallic core.)

The tilted field threw a wrench into some of *Voyager 2*'s other experiments. Edward C. Stone, chief project scientist of the Voyager mission, said navigators had hoped that by aiming for Neptune's geographic north pole, they would send the spacecraft across the converging magnetic-field lines of the auroral zone usually associated with the magnetic pole of a planet. Instead it entered the planet's magnetosphere—the ion-rich envelope created by the planet's magnetic field—along the converging lines, following them down toward the magnetic pole. This was dumb luck: according to Stone, no probe has ever flown that route before on any other planet, including the earth.

Voyager 2 did sight auroras in Neptune's atmosphere, but they were spread over a wide region rather than forming well-defined ovals around the magnetic poles, as on the earth. Auroras were also seen on Triton. Andrew Cheng of the Low-Energy Charged-Particle Team reported that charged particles in Neptune's radiation belts appear to plunge into Triton's atmos-

phere with sufficient energy to generate the ultraviolet auroras that were observed there.

In a mission filled with unexpected twists, one of the most dramatic was the resolution of the quest for the "lost arcs." Back in 1984 telescopes on the earth detected what appeared to be incomplete rings, or ring arcs, around Neptune. If partial rings indeed existed, they would be the first to be seen around any planet. In early August *Voyager 2* seemed to confirm the presence of arcs, but as the spacecraft closed in on its target it began to detect wispy segments between the arcs, and by August 24 the imaging team announced that the arcs were part of a complete outer ring. A remarkable time-lapse image revealed clumps of fine dust no more than 10 or 20 kilometers across embedded in one arc. Scientists have so far failed to come up with a plausible explanation for how the arcs formed. Other images revealed that Neptune has four rings altogether. The dust making up the rings is thought to be the debris thrown off over the eons when micrometeorites smashed into the moons.

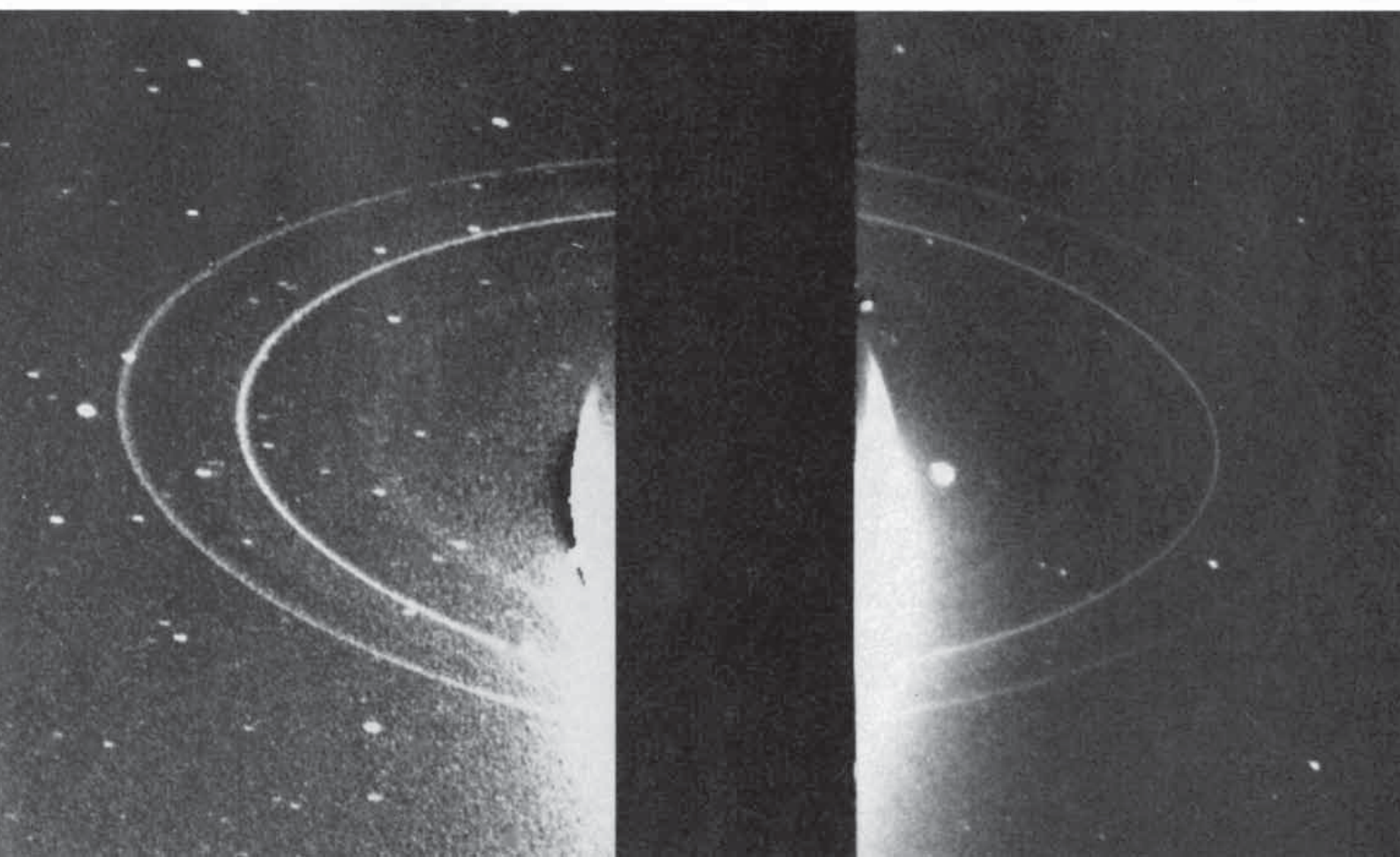
Observations of starlight being occulted by the outer ring indicated that it has a dense core about 17 kilometers across, surrounded by a diffuse halo of dust about 50 kilometers across. As *Voyager 2* crossed the plane of the ring about one hour before its closest approach to the planet, the plasma-wave detector transmitted a barrage of radio pulses generated by dust particles as they struck the spacecraft and vaporized into microscopic puffs of plasma. The hailstorm of pulses played back on audiotape the following morning by Donald J. Gurnett, head of the plasma-wave team, indicated as many as 300 strikes per second, or one particle per 300 cubic meters—comparable to the dust in Saturn's ring plane.

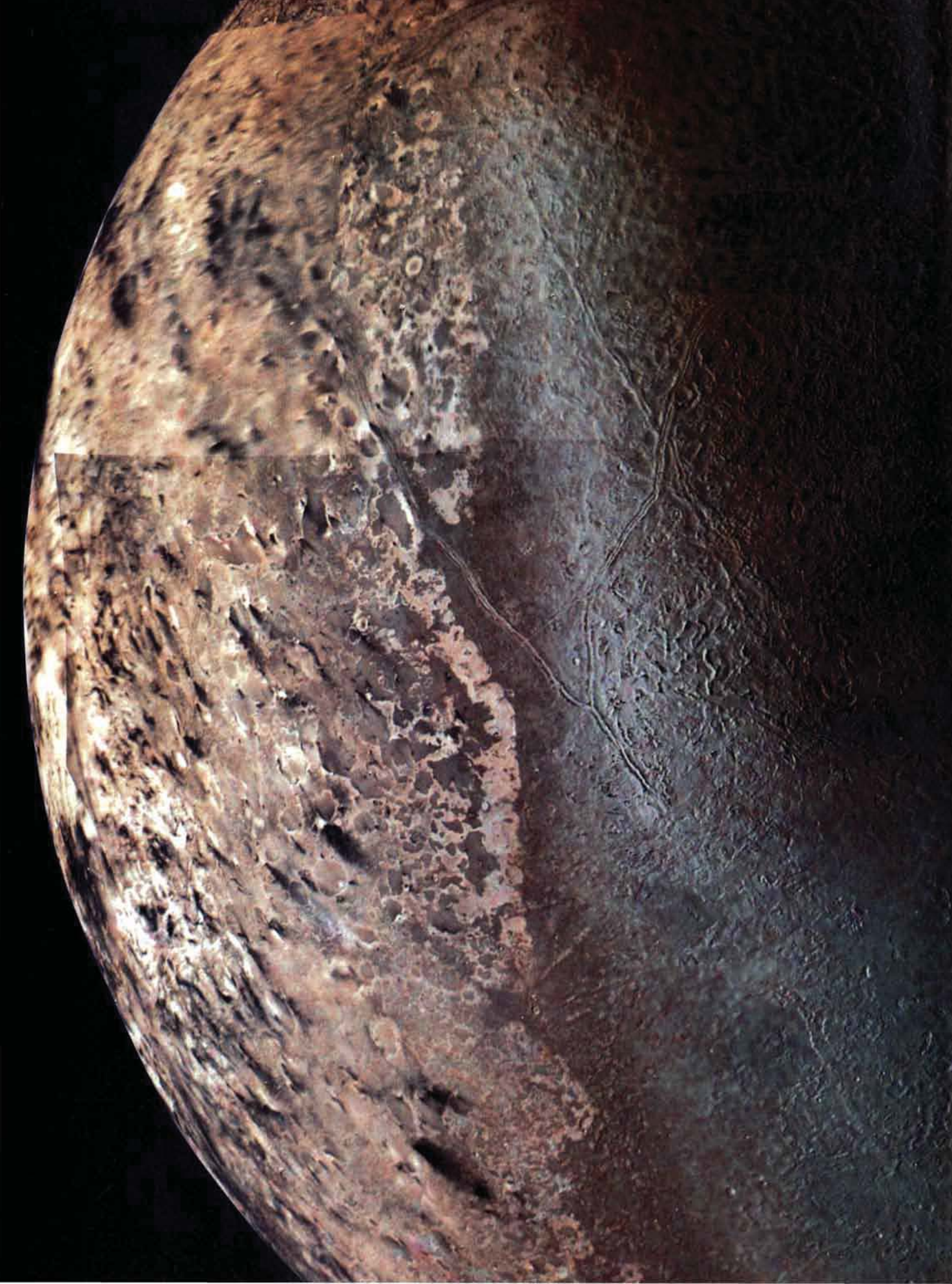
Two of Neptune's moons, Triton and Nereid, were known from terrestrial observations. *Voyager 2* found six new satellites, temporarily catalogued as 1989 N1 through 1989 N6. These dark, misshapen chunks range from 50 to 200 kilometers in diameter—too small to pull themselves into a sphere through gravity. *Voyager*'s grainy images of the meteor-battered bodies indicate that the small moons have remained essentially unmelted since the time they were formed.

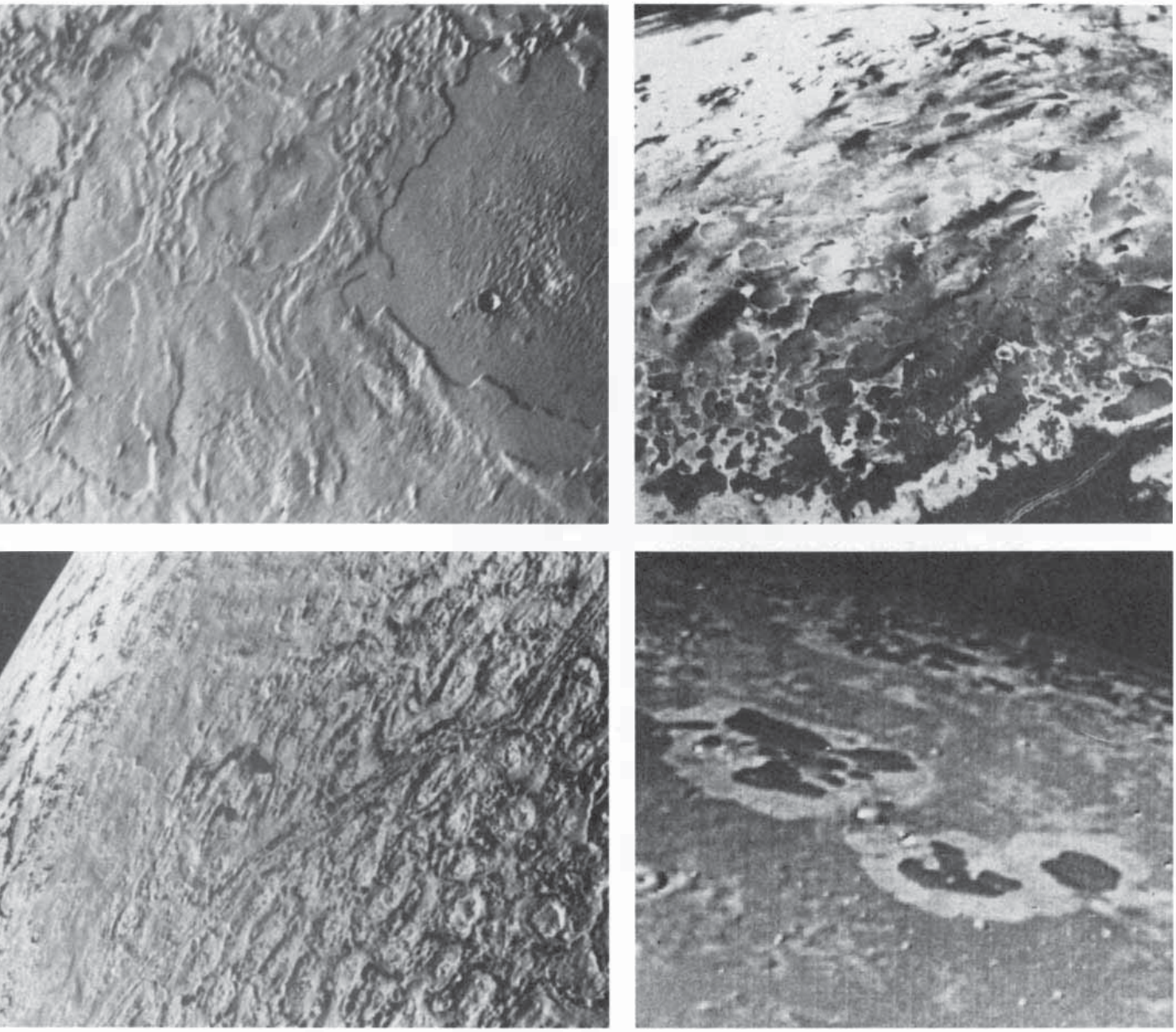
All of the newly found moons orbit near the equatorial plane of Neptune and in the same direction as the planet rotates. The orbital planes of Triton and Nereid, in contrast, are tilted by 20 and 30 degrees, respectively, and Triton orbits in the retrograde direction—the only large moon in the solar system to do so. The sharply tilted orbits suggest that these moons did not condense from the same matter as the planet but instead are foreign bodies that tumbled into Neptune's gravitational embrace. Dale P. Cruikshank of the Infrared Radiometry and Spectrometry Team observed that Nereid closely resembles a distant asteroid called Chiron. "Nereid could have been a cousin to Chiron," he said. "These could be the planetesimals from which the planets evolved."

If scientists knew little about Neptune before the *Voyager 2* flyby, they knew even less about its largest moon, Triton. As one of the Triton investigators put it: "We knew it was there, and we knew what it was called." In the days leading up to the encounter, *Voyager 2* transmitted teasing snapshots of Triton: a bruised, pinkish ball hinting at a spectacular geologic history. On the night of August 24, scientists stocked up on tortilla chips and coffee to sustain them until dawn, when the images from

***COMPLETE RINGS** can be seen in a pair of magnificent backlit images. There are two bright rings, a fainter inner ring and a diffuse sheet that may descend to Neptune's cloud tops. The planet itself was left out, accounting for the black strip in the middle.*







"A WORLD UNLIKE ANY OTHER" is how scientists described the tortured moon Triton, seen in a composite of a dozen high-resolution images **(opposite page).** ***The large south polar cap on the left side of the image may consist of a slowly evaporating crust of nitrogen ice deposited during the previous winter, some 80 years ago. Gigantic fissures scar the moon's face. Frozen lakes*** **(top left)** ***may have been melted by volcanism. Plumes of dark material over the polar frost may be evidence of more recent volcanism*** **(top right).** ***Cantaloupe-like terrain*** **(bottom left)** ***may have been created by local melting and deformation of the surface. Dark patches surrounded by a bright rim*** **(bottom right)** ***leave scientists still stumped.***

the spacecraft's closest approach to Triton would reach the earth. In the pressroom, reporters slumped over typewriters or paced expectantly in front of the monitors.

At 3:40 A.M., the first of the black-and-white images flashed on the screens. People leapt to their feet and rushed up to the monitors, exclaiming and pointing as the remarkably sharp pictures disclosed crenulated landscapes, vast canyons, craters and peaks. Each new image was more bizarre than the last. "It looks like tripe," someone said. Others suggested "cantaloupe" and "cellulite." It was, as a tired, happy Ed Stone remarked later that morning, "a night to remember."

Triton proved to be 2,720 kilometers in diameter—somewhat smaller than the earth's moon. Ices of methane and nitrogen encrust its polar cap, which reflects away so much sunlight that the temperature is a mere 37 kelvins, making Triton "the coldest object we have seen in the solar system," said Roger Yelle of the ultraviolet spectrometry team. Even so, the moon's tilted rotational axis and tilted orbital plane give rise to extremes of season. The south polar cap, now at the height of its 41-year-long summer, has evaporated away at many spots along its border.

Triton's atmosphere is exceedingly thin, about 100,000 times thinner than the earth's, and consists mainly of nitrogen. A magnified view of the moon's limb (its silhouetted edge) revealed that the atmosphere, thin as it is, is still sufficient to support a haze of small particles from about five to 10 kilometers above the surface. The atmosphere's temperature rises to about 100 kelvins at an altitude of 600 kilometers. Scientists say the phenom-

***VOYAGER'S LAST LOOK** at Neptune caught the crescent of Triton hovering near the looming belly of the planet. The image was taken three days after the closest approach, as the spacecraft was plunging southward out of the solar system.*

enon is unlike a temperature inversion in the earth's atmosphere. The heating in Triton's atmosphere is occurring at a higher altitude, and so far no one understands what could be causing it.

Much curiosity centered on the dark smudges resembling wind streaks on Triton's south polar cap. Laurence A. Soderblom of the imaging team raised one of the biggest stirs of the encounter by suggesting that the streaks were caused by volcanic eruptions or geysers. Temperatures and pressures near Triton's surface would allow some internal heat source to raise subsurface liquid nitrogen to pressures at which it would explode, he said. As the nitrogen was ejected into the atmosphere, it might have swept along darker carbon compounds from the crust. The dust could have wafted downwind and blown onto the frost. Soderblom suggested that such eruptions might be occurring all over the moon and that it is the icy ground cover that makes the plumes visible only on the south polar cap. Similar plumes of sulfur dioxide were seen on the Jovian moon Io, Soderblom noted. "This is a crazy idea, and it's probably wrong," he said, "but it's the best we have in the meantime."

Just to the north of the polar cap lies a vast tract of evenly sized circular depressions and ridges that resembles nothing so much as the rind of a cantaloupe. "The area has been faulted and deformed an indescribable number of times," Soderblom said. The surface bears noticeably fewer craters than an adjacent region, which indicates that it is probably the youngest terrain on the moon. Fissures slash the surface like superhighways, meeting in gigantic X's and Y's. Viscous material, perhaps a slush of water laced with ammonia, appears to have forced its way up into some of these fissures, forming central ridges and in some cases overflowing onto the surrounding plain.

Lying within this terrain are frozen lakes edged with a series of terraces, as though the level of the lakes had changed as a result of repeated freezing and melting driven by volcanic heat. Such terraced formations are common in Hawaiian volcanoes, Soderblom said. The lakes on Triton

must have once been filled with a low-viscosity liquid, because their frozen surface is level. Yet in frozen form the substance must be extremely rigid in order to sustain kilometer-high terraces. Methane, nitrogen and carbon monoxide are implausible candidates, said Steven K. Croft, a geologist at the University of Arizona, because in their frozen form they would flow like glaciers. Water ice, however, is as rigid as rock at the temperatures found on Triton and is "almost certainly" the material out of which the lakes formed, he said.

These signs of past volcanism prove that Triton was once a hotter place, presumably because it had an unusual origin. Triton may once have been an independent planet rather like Pluto, which it resembles in size and possibly composition—it contains more rock than do the other icy satellites. Later, Triton was captured by Neptune; as it gradually settled into its current circular orbit, tidal friction would have melted the moon and driven the volcanism until perhaps from one to two billion years ago. "It's likely that we're seeing the frozen imprint of that earlier era," Stone said.

Voyager's reconnaissance of Triton ended an extraordinary epoch of planetary exploration. In the 12 years since they were launched, the *Voyager* spacecrafts have contributed more to the understanding of the planets than three millennia of earthbound observations (and at a cost of only $2.40 per U.S. citizen for the entire show). Science now has "nothing less than the encyclopedia of the planets," Stone exulted.

Voyager 2 is now heading southward out of the plane of the planets at an angle of about 50 degrees. *Voyager 1* veered northward after the Saturn flyby. The spacecrafts' plutonium power sources are expected to sputter out around the year 2015. By that time scientists hope the *Voyagers* will have encountered the heliopause—the true edge of the solar system, where the solar wind collides with the interstellar medium. They will then drift sightless and voiceless through the eons, a testament to the questing spirit of the humans who launched them.

JUNE KINOSHITA is International Coordinating Editor and a member of the Editorial Board of *Scientific American*. She thanks Edward C. Stone, professor of physics at the California Institute of Technology and chief project scientist for the Voyager mission, for his assistance in preparing this article.