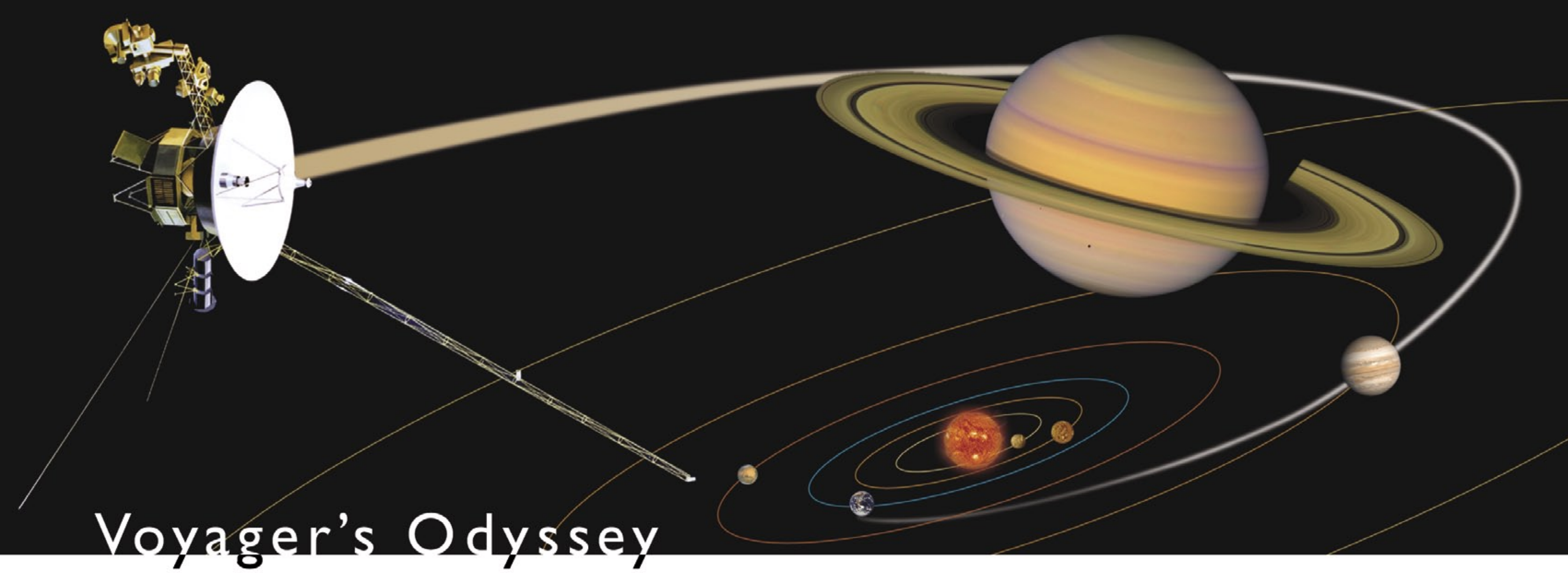


Voyager's Odyssey

by Marcus Woo

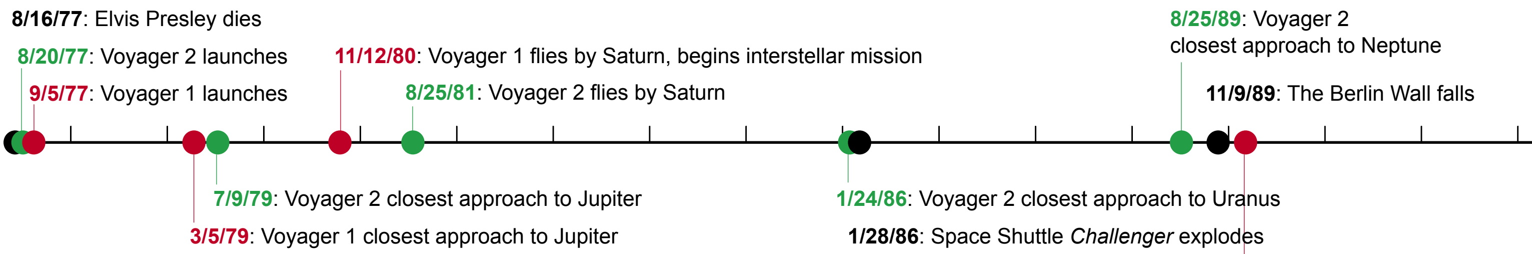
Right: Voyager 2 launches from the NASA Kennedy Space Center at Cape Canaveral in Florida. Far right: Saturn's moon Mimas.

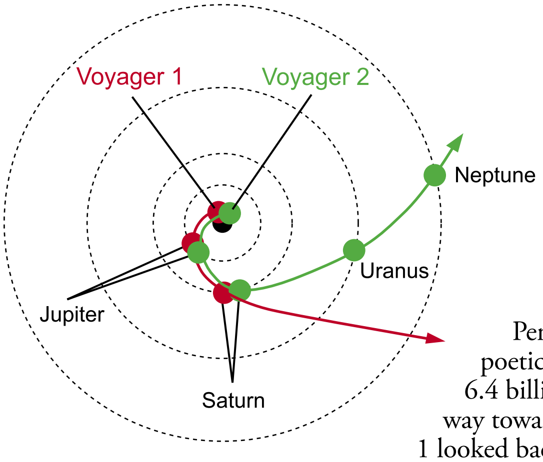
Four days after Elvis Presley died, a rocket blasted off into the blue skies above Cape Canaveral. While America was mourning the loss of a cultural icon, the Titan III-Centaur was propelling the first of two robotic craft toward their own iconic status—symbols of discovery, exploration, science, and the human spirit. Voyager 2 lifted off on the morning of August 20, 1977, and its sister ship would launch on September 5. They would explore alien worlds, capturing the imaginations of scientists and the public as they ventured on a quest as epic as any in history.

"Voyager is undoubtedly the ultimate mission of discovery," says Edward Stone, the Morrisroe Professor of Physics, vice provost for special projects, and Voyager project scientist. "There will never be another mission that will see so many new things for the first time."

For more than a decade, as the Voyagers hopped from planet to planet and moon to moon, they returned jaw-dropping images, showing the solar system to be a place more wild and wonderful than imagined. The mission would reveal, for instance, the violent, churning clouds of Jupiter and the winds of Neptune, which can blow at nearly 1,500 kilometers per hour. The Voyagers would discover rings on Jupiter and Neptune, and find even more than those previously known around Saturn and Uranus. They found volcanoes on Jupiter's pockmarked moon Io, with plumes bursting up hundreds of kilometers into space, and moons with bizarre surfaces that would make any geologist swoon. When the monitors at JPL's Von Karman auditorium displayed the first image of Saturn's moon Mimas, showing its enormous crater, somebody reportedly exclaimed, "My God, it's the Death Star!"

Voyager shook our view of Earth's place in the solar system. Our world was no longer the only body alive with earthquakes, volcanoes, and geysers. Our atmosphere with its storms, winds, and clouds was nothing compared with those of the outer planets. Most scientists, including Andrew Ingersoll, the Anthony Professor of Planetary Science and an atmospheric scientist on the Voyager team, hadn't anticipated such diversity. "I only had Earth to think about, and Earth didn't provide me with enough imagination to guess what we would see," Ingersoll says. "I couldn't imagine how rich it could be."





Top: A timeline of notable dates during the Voyager mission. Above: The Voyager spacecraft trajectories from Earth to the outer planets and beyond.

Perhaps the most profound and poetic image was of Earth from 6.4 billion kilometers away. On its way toward interstellar space, Voyager 1 looked back toward us and snapped a shot of a bright speck floating in space, filling just over a tenth of a pixel. It was humanity's humble home and, as Carl Sagan famously described it, nothing but a pale blue dot.

More than 30 years after launch, having made one astounding discovery after another, and having penetrated popular culture with appearances on *Star Trek: The Motion Picture* as well as on *Saturday Night Live* and *The X-Files*, Voyager still hasn't finished telling its story. Like human explorers who left old worlds for new, both robots are leaving the relative familiarity of the solar system for the great expanse of interstellar space. Voyager 1 is at the edge of the heliosphere, the bubble formed by the solar wind, and is speeding at over 61,000 kilometers per hour toward the heliopause, the boundary separating the bubble and interstellar space. Voyager 2 is not far behind.

After decades that have seen the death of Elvis, the birth of the Internet, the fall of the Berlin Wall, two space shuttle disasters, five presidents, and two Iraq wars, Voyager's odyssey endures. The secret to its success? Lots of ingenuity and a dash of luck.

An Unshakable Belief

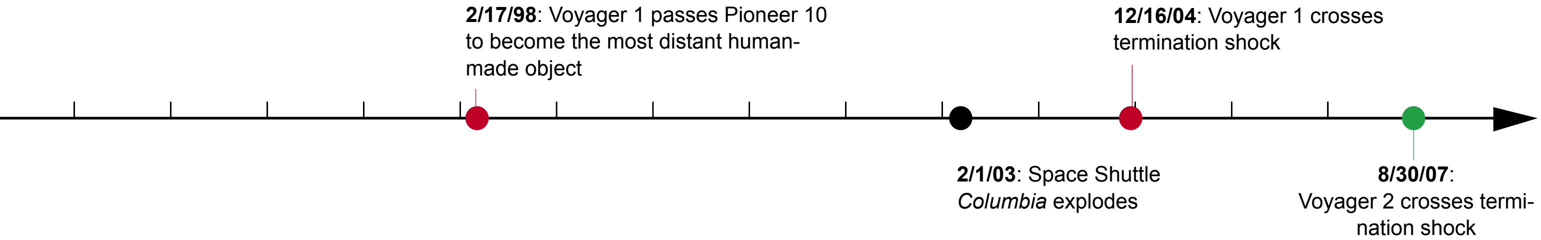
The Voyager mission depended on a planetary alignment that occurs once every 176 years, which graduate student Gary Flandro (MS '60, PhD '67) discovered in 1965. With the four gas giants lined up, Voyager could use each planet as a gravitational slingshot to shorten travel time to the next—a technique developed at JPL by UCLA graduate student Michael Minovitch in 1961. Mariner 10 first used the method in 1973, getting a boost from Venus on its way to Mercury. Instead of 30 years, Voyager's journey to Neptune took 12. But such a trip would never have happened if the alignment had come a few years earlier, before technology could turn the dream into reality.

The mission eventually became known as the Grand Tour, but the moniker first belonged to its predecessor, a more ambitious mission that aimed to send two pairs of spacecraft to explore all of the outer planets and Pluto, and would last for at least 12 years. Scientists and engineers began designing the mission in the late '60s and early '70s, developing the most advanced craft ever built at the time. But when the project was killed for budgetary reasons, researchers recast the mission as one that would stop after Saturn, needing to last only four years. Billed as a continuation of the Mariner program, they called it MJS '77, for Mariner-Jupiter-Saturn 1977. Later, the team would rename it Voyager.

Even though their stated goal was Saturn, many wanted to achieve the Grand Tour. "There were some of us that had an unshakable belief that with the MJS '77 spacecraft we could and should do more than Jupiter and Saturn," says Rochus "Robbie" Vogt, the Avery Distinguished Service Professor and Professor of Physics, Emeritus, who served on the Voyager science mission team. As the principal investigator of the cosmic-ray experiment, Vogt was especially interested in interstellar space, and made no secret of his ultimate goal.

During the design phase, Vogt kept pushing for more hydrazine, which powered the small jets that steered the spacecraft during flight and kept its radio antenna pointing at Earth. In a robot where every ounce of weight was a trade-off, negotiation wasn't easy. "I became known for my obsession with hydrazine," Vogt says. "It's just how clever you are with the money you're given with optimizing various trade-offs to get the things you want." In the end, he succeeded, but going farther than Saturn was still anything but certain.

At the time of the launch, the space age was only 20 years old, Stone reminds us. No one had any



experience in planning a 20- or 30-year mission. But once Voyager 2 got to Saturn in 1981, the team pushed forward, and the mission became the Voyager Uranus Interstellar Mission. "We gave it our everything to make it possible, and it worked," Vogt says. "You have to be both very good and lucky. You need both, but if you're very good and do a very good job, you need less luck."

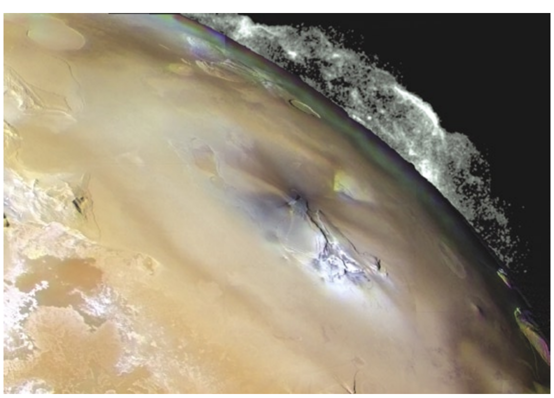
Stone attributes the spacecraft's longevity to its robust design, which the team began planning in 1972. Pioneer 10, a more primitive craft that arrived at Jupiter in 1973, found radiation levels to be 1,000 times higher than expected. Engineers then beefed up the circuitry in the Voyagers to withstand such radiation. Another crucial component was the radioisotope thermoelectric generators, which depended on the 87.7-year half-life of plutonium-238 for long-lasting power. With the sun so far away, solar power wouldn't have cut it.

"There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."—Carl Sagan

Although primitive by today's standards, the computers on board the Voyagers were key advancements over Mariner technology. Because of the vast distances from Earth, commands would have taken hours to travel between craft and engineers. Additionally, during the years of cruising time, the budget couldn't afford a full-time team to oversee every spacecraft detail. Both factors meant the Voyagers needed to fly solo at times, with unprecedented independence to fix themselves should they encounter problems.

When Voyager 2 became a mission to Uranus, the team had to redesign and adjust hardware and overhaul software. The ability to reprogram spacecraft wasn't new, but it was essential to handle the extended missions. The new distances—Uranus, for example, is nearly twice as far from the sun as Saturn—meant communication would be an even greater challenge. Engineers rewrote software to make data transfer more efficient, and uploaded it onto the robot from Earth, a major accomplishment. The transmitter, meanwhile, radiates only 23 watts of power—about as powerful as a refrigerator light bulb. To increase sensitivity for the Grand Tour, engineers enlarged the ground-based antennas around the world that made up NASA's Deep Space Network.

Of course, everything wasn't smooth and easy—this was still rocket science, after all. No one had ever flown such a complicated spacecraft over such a long distance, and problems were inevitable as the team got to know the Voyagers. "The spacecraft was well designed," Stone says. "We just had to learn how to use it and learn how to program it." Still, the mission had some close calls. Voyager 1 launched two weeks after Voyager 2, and the second Titan rocket did not burn all of its fuel. As programmed, the upper-stage Centaur rockets then burned longer to put it on course—but with only 3.4 seconds of fuel left. Bruce Murray, professor of planetary science and geology, emeritus, Voyager scientist, and director of JPL at the time, would later realize that had Voyager 2 used the underperforming rocket, it would not have had the boost needed to reach Uranus. "The opportunity of the century would have passed us by," he wrote eventually.

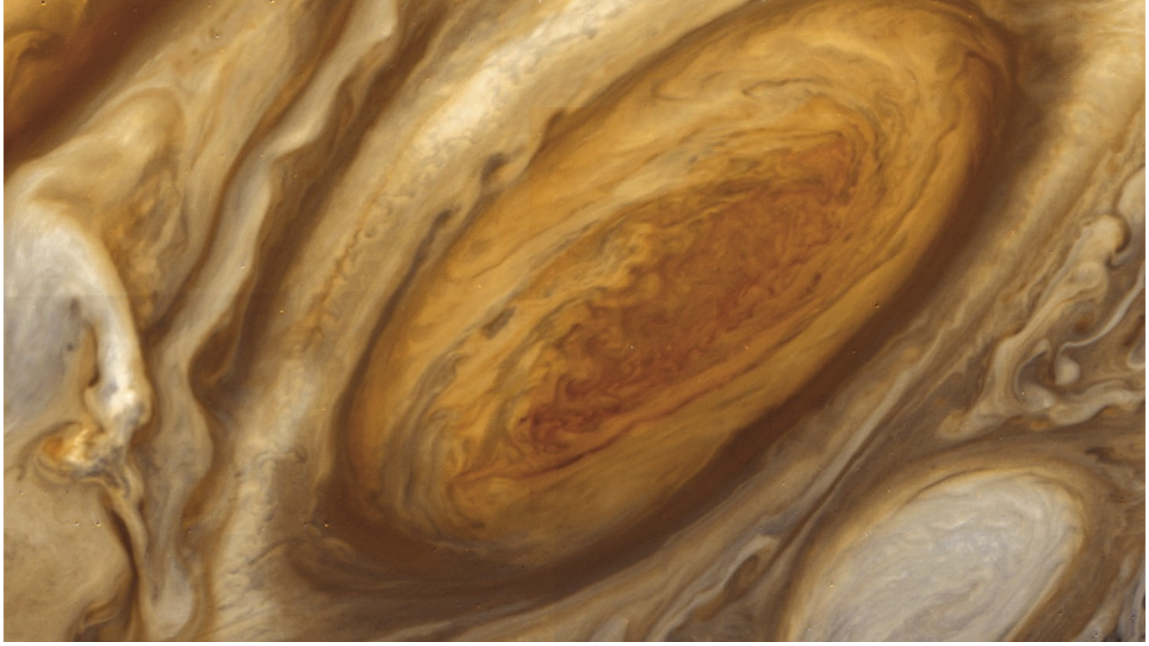


The eruption of Pele on Jupiter's moon Io. The volcanic plume rises 300 kilometers above the surface in an umbrella-like shape. The plume fallout covers an area the size of Alaska.

Let the Discoveries Begin

Voyager 1 arrived at Jupiter in 1979, and when it approached the moon Io in March, it would make perhaps its most shocking discovery. Instead of another dead, cratered world like our moon, Io was chock-full of volcanoes ejecting plumes of sulfur at several hundred degrees Celsius.

Io is slightly larger than our moon, and conventional wisdom says that such a relatively small body



This photo of Jupiter was taken by Voyager 2 and shows Jupiter's Great Red Spot, which is three times as large as Earth. None of the structure and detail evident in these features had ever been seen from Earth.

should have cooled long ago, leaving it geologically dead. But tidal forces from Jupiter and fellow satellites Europa and Ganymede squeeze and tug at Io, creating friction and the heat needed to power more than 100 volcanoes. In fact, it's the most volcanically active body in the solar system. Stone calls Io's volcanoes the most memorable discovery of the mission. "It became symbolic of the surprises that were ahead of us as we continued our journey of exploration," he says.

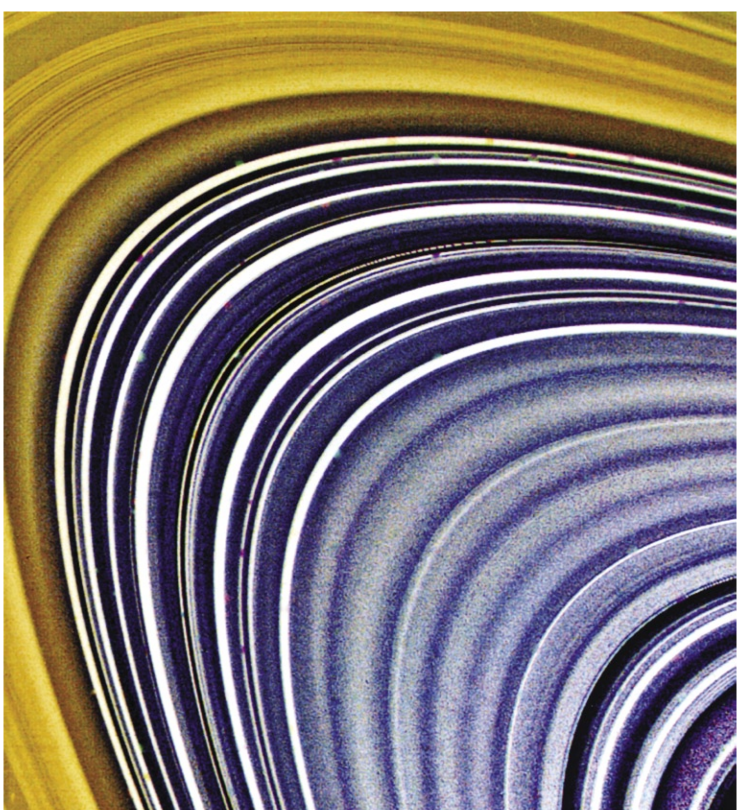
Voyager found the volcanoes with the help of a little luck and an alert engineer. The spacecraft had already flown past Io, and most of the team was resting in preparation for the next encounter. "People were exhausted from lack of sleep," Ingersoll recalls. "People were sleeping in their cars in the JPL parking lot, stretched out on the floor in the lab." Meanwhile, engineer Linda Morabito-Kelly was looking at some of the navigation images used to steer Voyager. She noticed a large, crescent-shaped object sticking out of Io. After ruling out calibration errors and other possible explanations, she realized this object was real, and, in fact, an erupting volcano. As Ingersoll says, "That was how the first volcano was discovered—not by the science team, who were all asleep in their cars at that point, but by one of the engineers."

For Ingersoll, an atmospheric scientist, the highlight of Jupiter was the turbulence surrounding features like the famous Great Red Spot, a giant storm that has been raging for at least 300 years. "I had a biased thinking that the flow in the vicinity of those spots was laminar, smooth, and well organized," he says. "It blew me away when the first close-up images came in, and it was not like that at all!" Scientists thought turbulence near the spot would disrupt it, but instead the adjoining clouds churn and swirl. Ingersoll likens the atmosphere to a food chain, and turbulence feeds the Great Red Spot the energy needed to maintain its structure.

The gas giants' atmospheres continued to surprise Ingersoll and the rest of the science team with the arrival of Voyager 1 at Saturn in 1980. Being roughly twice as far from the sun as Jupiter, Saturn receives a quarter of the sunlight. Scientists thought the reduced energy would translate to a calmer atmosphere. But astonishingly, Saturn's winds were even stronger than Jupiter's.

Saturn's most distinguishing feature is, of course, its rings. Voyager counted hundreds of small features within the main ones. It found odd patterns on the rings that looked like spokes. Scientists determined that the spokes were scattered sunlight, produced in a way that suggested they were made by dust specks a few hundredths of a millimeter wide. It also found "shepherding" satellites, small moons in inner and outer orbits around a ring. They give and extract energy to and from the ring, keeping it together as shepherds do with a flock. Previously, the DuBridge Professor of Astrophysics and Planetary Physics,

This view focusing on Saturn's C-ring (and to a lesser extent, the B-ring at top and left) was compiled from three separate images taken through ultraviolet, clear, and green filters. More than 60 bright and dark ripples are evident here.



Emeritus, Peter Goldreich, had predicted the existence of shepherding satellites around Uranus, which Voyager 2 later confirmed.

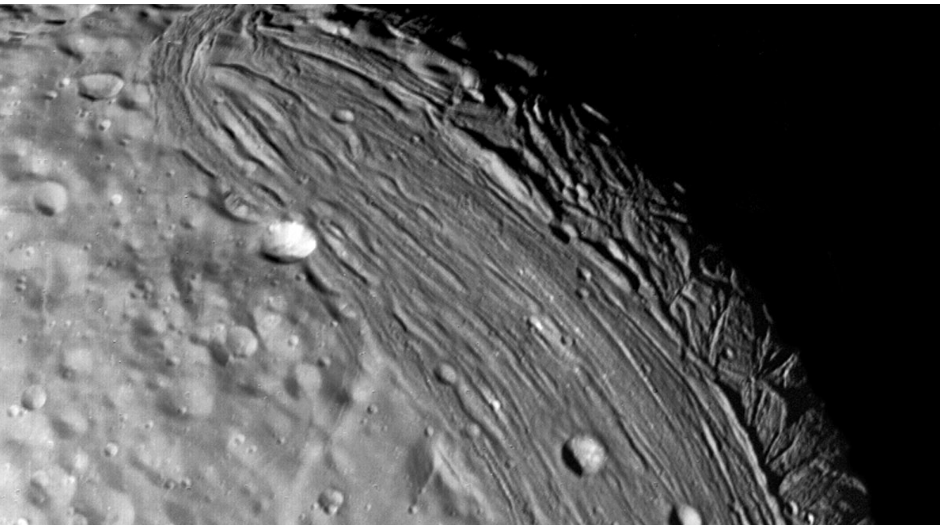
Voyager 1 then swung around for a shot of Saturn's largest moon, Titan, which boasted an atmosphere of organic molecules such as methane. Unfortunately, the clouds were too thick for cameras to penetrate. The route needed to reach Titan put Voyager 1 on a course for interstellar space at a 35-degree angle up from the plane of the solar system, ending its planetary mission. The dream of a Grand Tour became reality as Voyager 2 headed toward Uranus after whizzing by Saturn. But its arrival on January 24, 1986, would be overshadowed by a national tragedy when, four days later, the space shuttle *Challenger* exploded upon liftoff, a few minutes past 11:30 a.m. local time. Ironically, that morning's *New York Times* had run an editorial, written before the tragedy, touting Voyager's triumph and urging NASA to pursue robotic exploration instead of manned missions. "Voyager 2 shows space exploration at its best," it read. "If NASA wants lasting public support for a vigorous space program, the wonder of seeing new worlds will do it a lot more good than soap opera elevated to Earth orbit." After some soul-searching, the Voyager team gathered to celebrate another Voyager success. There was, after all, lots of exciting science to do.

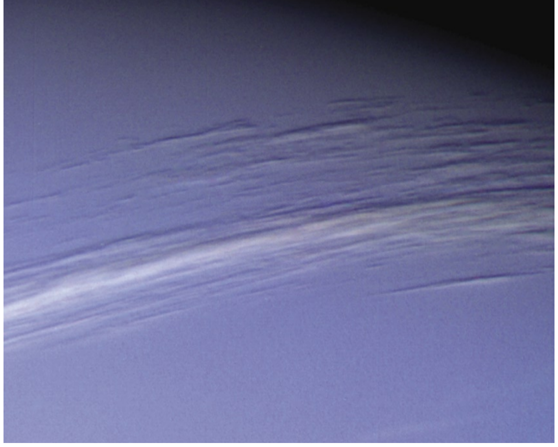
Uranus is tipped on its side more than 90 degrees, so that its north and south poles take turns facing the sun in summer and winter. Scientists wondered if the sun's energy might drive the atmosphere to flow from pole to pole, rather than the east-west direction of the planet's rotation. But Voyager observed the latter, showing that planetary rotation—and not the sun—was the atmosphere's controlling factor. "That was a real discovery," Ingersoll says. "I don't know if we could've guessed how it turned out."

If a tipped rotation axis weren't enough, Uranus's magnetic field axis proved to be slanted 60 degrees. Not only that, the magnetic axis was offset, instead of going straight through the planet's center.

The moons were just as perplexing as those of Jupiter and Saturn. Uranus's largest moon, Miranda, looked as if it had been taken apart and thrown back together, like a cubist painting. Sheer

Miranda reveals a complex geologic history; at least three terrain types of different age and geologic style are evident at this resolution.



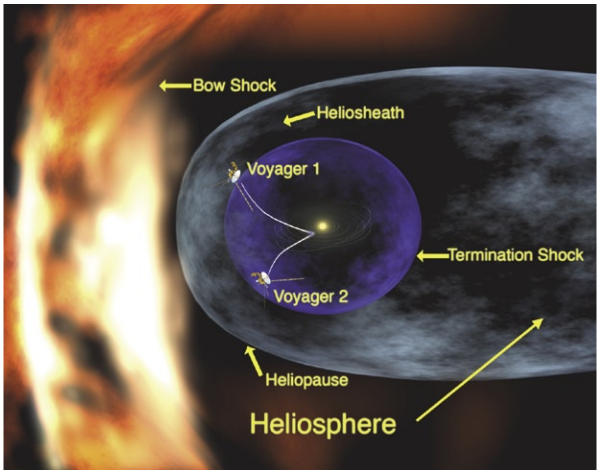


This image provides obvious evidence of vertical relief in Neptune's bright cloud streaks. Shadows can be seen on the cloud edges opposite the sun.

cliffs and canyons 15 kilometers deep covered its surface. Some scientists think a collision blew it apart before gravity reassembled it.

By late August 1989, Voyager 2 was fast approaching Neptune. In a couple of weeks, Hurricane Hugo would bear down on the Caribbean and the Carolinas. Scientists were tracking storms on Neptune as well, including the Great Dark Spot. Voyager had shown that the variability of Earth's atmosphere is the exception rather than the rule, so weather forecasting on the outer planets is a lot easier than on Earth. "The newspapers were giving twelve-hour forecasts trying to predict where Hugo would come ashore," Ingersoll recalls. To follow the Great Dark Spot, however, the team had to upload Voyager's instructions much sooner. "At the same time, we had to make predictions two weeks in advance about where the Great Dark Spot would be. We just used junior high school mathematics. We plotted the position of the Great Dark Spot over the preceding months, put it on a piece of graph paper, drew a straight line, and said, 'right there—that's where it's going to be.'"

As at previous encounters, Stone led daily press briefings, unveiling the latest pictures and findings. Neptune was the last stop of the Grand Tour, and in the months of the approach, scientists planned to end with a big press conference. "We wanted to go out in style," Ingersoll says. But many were nervous—what if the moons were dull, and there was nothing except for four storms they already knew existed? Cornell's Carl Sagan, a member of the imaging team, told him not to worry, Ingersoll remembers. If there was nothing but four storms, then that's all they would talk about. But with all the surprises Voyager had produced so far, maybe they should have known better by then. In addition to the swirling storms, they found blasting winds, discovered rings and ring arcs, and detected a tilted magnetic field like Uranus's. Neptune's moon, Triton, had faults, ridges, volcanic calderas, and erupting geysers, all on a frozen world without the gravitational squeezing that powered Io. "It was a fantastically interesting place," Ingersoll says.



This illustration shows the locations of Voyagers 1 and 2. Voyager 1 has ventured into the heliosheath, the region where the slowing solar wind presses out against the incoming interstellar gas. Voyager 2 joined its partner when it crossed the termination shock at the end of August 2007. (NASA/Walt Feimer)

Worthy of Legend

While the engineers, overcoming problems from billions of kilometers away, were heroes, Ingersoll says, "The other heroes were the planets themselves—they came through. They came through with better stuff than we could have anticipated." Because of Voyager, these distant planets and moons were transformed from distant dots to dazzling characters, heroes worthy of their legendary namesakes from the pages of Roman mythology and Shakespeare. "Every day, we were looking at things no one had seen before," Stone says. "It was a period of intense discovery." Each planetary approach lasted about three months, and during this time, raw images would flash on the monitors all over JPL and NASA. "People would be sitting in the cafeteria and [looking at the monitors] say, 'God, what is that?'" Ingersoll says. "It was the best science I've ever been involved with."

The mission itself has become legendary. During its planning stage in the early '70s, Voyager rode the confidence that stemmed from beating the Soviet Union to the moon in 1969. But moonwalks rapidly became commonplace, and with the Vietnam War, Watergate, continuing Cold War conflicts, and an arms race, American optimism waned. "The climate changed in this country when Americans developed doubts about themselves," Vogt says. Voyager, on the other hand, with its message to the stars in the form of a golden record encapsulating Earth in sounds, music, and pictures, represented the human spirit. In a time of uncertainty and mistrust, when the specter of nuclear war was real, Voyager exemplified the best of humanity.

Space, as an emblem of brighter possibilities, remained embedded in the American psyche. Along with the popularity of the *Star Wars* and *Star Trek* films in the late '70s and the '80s, Voyager did its part to fuel the fascination with space. "It resonated with this idea that space is a future for humanity via robotics or humans," Stone says. "Voyager was symbolic of humans reaching out into space."

The Final Chapter?

Voyager 1 crossed what's called the termination shock in December 2004. The solar wind spews outward from the sun at speeds of 300 to 700 kilometers per hour, and as it approaches the interstellar wind—streams of particles from other stars—it abruptly slows, forming the termination shock. Voyager 2 just crossed the shock at the end of August 2007. Both spacecraft are now exploring the heliosheath, the outer layer of the heliosphere. At 15 billion kilometers away, Voyager 1 is the most distant human artifact. No one knows for sure how big the heliosphere is, but scientists estimate the spacecraft will leave the teardrop-shaped bubble, cross the heliopause, and enter interstellar space in about 10 years. The Voyagers will then be cruising through particles not from the sun, but from other stars and the stellar explosions called supernovae.

Although Vogt left the mission to become Caltech's provost in 1983, he still keeps tabs on Voyager's findings as it approaches the goal he envisioned more than 30 years ago. "I wanted to get the hell out of the solar system and measure pristine, galactic stellar stuff—stuff we are made of," he says. The Big Bang created only the lightest elements, from hydrogen through beryllium. Anything heavier was created in the cores of stars and during supernovae. Spread across the universe by these massive blasts, the brand-new atoms eventually became everything from planets and moons to humans and rubber ducks. "This is something extremely romantic, to think that we are star stuff, that at one time the atoms we are made of were in a star that exploded, expelled us, and ultimately became the solar system and organic stuff," Vogt says.

In the solar system, Vogt's cosmic-ray instrument measured the solar wind and magnetic fields. Now, in addition to understanding supernovae, it will help scientists learn how the sun interacts with the surrounding interstellar medium. In the end, Voyager's mission has always remained the same: to learn what's out there.

Even when the two spacecraft exhaust their power and communication with Earth stops, they will continue hurtling through space. Maybe they will encounter another civilization, and, if they do, they'll have quite a story to tell. □

PICTURE CREDITS: 19-23—NASA/JPL-Caltech; 19-21—Doug Cummings; 24—NASA/Walt Feimer