



## Voyager to the Outer Planets and Into Interstellar Space

The twin spacecraft Voyager 1 and Voyager 2 were launched by NASA in separate months in the summer of 1977 from Cape Canaveral, Fla. As originally designed, the Voyagers were to conduct close-up studies of Jupiter and Saturn, Saturn's rings, and the larger moons of the two planets. Now, more than 35 years later, they have explored four planets between them, and Voyager 1 is currently speeding through the space between stars.

To accomplish their two-planet mission, the spacecraft were built to last five years and travel 10 astronomical units, or 10 times the distance from the sun to Earth. But as the mission went on, and with the successful achievement of all its objectives, the additional flybys of the two outermost giant planets, Uranus and Neptune, proved possible — and irresistible to mission scientists and engineers at the Voyagers' home at NASA's Jet Propulsion Laboratory in Pasadena, California.

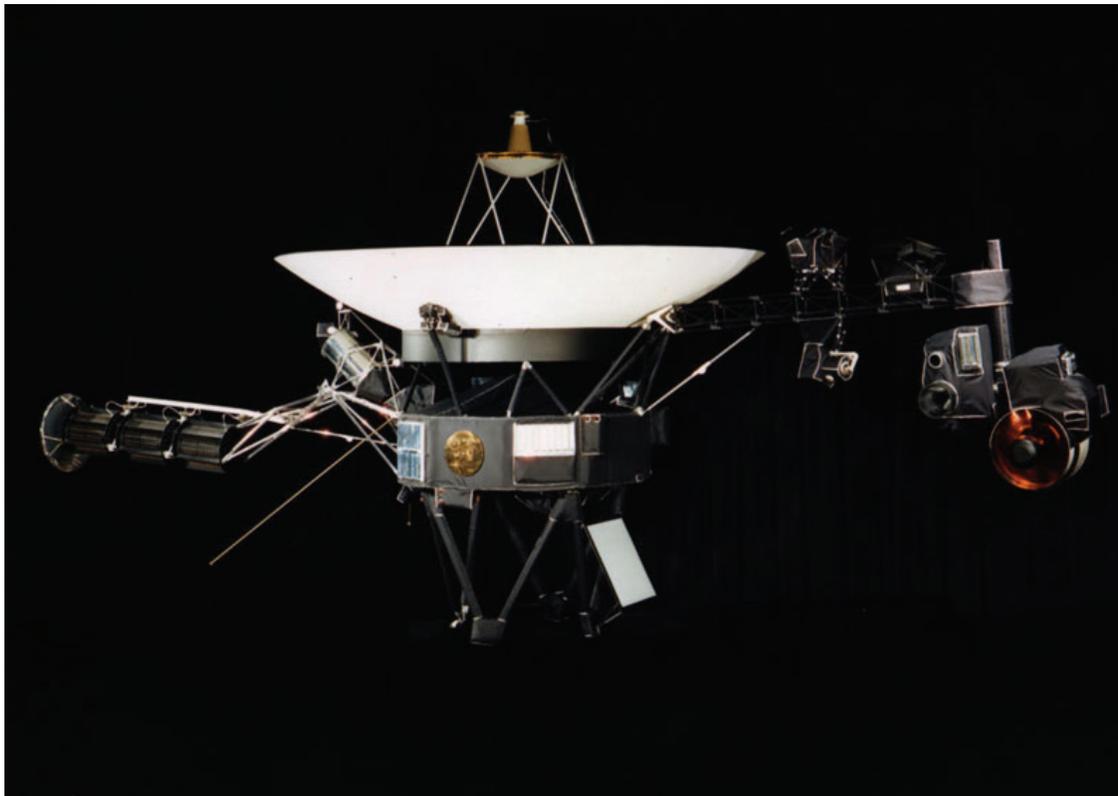
As the spacecraft flew across the solar system, remote-control reprogramming was used to endow the Voyagers with greater capabilities than they

possessed when they left Earth. Eventually, between them, Voyager 1 and 2 would explore all four giant outer planets of our solar system, 48 of their moons, and the unique systems of rings and magnetic fields those planets possess.

Had the Voyager mission ended after the Jupiter and Saturn flybys alone, it still would have provided the material to rewrite astronomy textbooks. But multiplying their mileage by more than 10 since then, the Voyagers have returned to Earth information over the years that has revolutionized the science of planetary astronomy and heliophysics. They have helped scientists resolve key questions while raising intriguing new ones about the origin and evolution of the planets in our solar system and the way our solar system interacts with the surrounding interstellar medium.

### Mission Concept

The Voyager mission was designed to take advantage of a rare geometric arrangement of the outer planets in the late 1970s and 1980s. This layout of Jupiter, Saturn, Uranus and Neptune, which occurs



about every 175 years, allows a spacecraft on a particular flight path to swing from one planet to the next without the need for large onboard propulsion systems. The flyby of each planet bends the spacecraft's flight path and increases its velocity enough to deliver it to the next destination. Using this "gravity assist" technique, the flight time to Neptune was reduced from 30 years to 12.

While the four-planet mission was known to be possible, it was deemed to be too expensive to build a spacecraft that could go the distance, carry the instruments needed and last long enough to accomplish such a long mission. Thus, the Voyagers were funded to conduct intensive flyby studies of Jupiter and Saturn only. More than 10,000 trajectories were studied before choosing the two that would allow close flybys of Jupiter and its large moon Io, and Saturn and its large moon Titan; the chosen flight path for Voyager 2 also preserved the option to continue on to Uranus and Neptune.

From the NASA Kennedy Space Center at Cape Canaveral, Fla., Voyager 2 was launched first, on August 20, 1977; Voyager 1 was launched on a faster, shorter trajectory on September 5, 1977. Even though it launched second, this spacecraft would reach Jupiter first, and so it was named Voyager 1. Both spacecraft were delivered to space aboard Titan-Centaur expendable rockets.

The prime Voyager mission to Jupiter and Saturn brought Voyager 1 to Jupiter in 1979 and Saturn in 1980, while Voyager 2 flew by Jupiter in 1979 and Saturn in 1981.

Voyager 1's trajectory, designed to send the spacecraft closely past the large moon Titan and behind Saturn's rings, bent the spacecraft's path inexorably northward out of the ecliptic plane — the plane in which most of the planets orbit the sun.

After Voyager 2's successful Saturn encounter, it was shown that Voyager 2 would likely be able to fly on to Uranus with all instruments operating. NASA provided additional funding to continue operating the two spacecraft and authorized JPL to conduct a Uranus flyby. Subsequently, NASA also authorized the Neptune leg of the mission, which was renamed the Voyager Neptune Interstellar Mission.

Voyager 2 encountered Uranus on January 24, 1986, returning detailed photos and other data on the planet, its moons, magnetic field and dark rings. It made its closest approach to Neptune on August 25, 1989.

Then Voyager 2 flew over Neptune's north pole and was deflected southward, below the ecliptic plane and onto a course that took it past Neptune's moon Triton, with an ultimate goal of departing our solar system, which has now been achieved. The part of Voyager's mission that has taken it beyond the planets into the space between stars is known as the Voyager Interstellar Mission.

Voyager 1 has now left the heliosphere, the space filled with plasma (or ionized gas), the sun blows around itself as solar wind. Its instruments show that Voyager 1 is the first spacecraft to move beyond the solar wind — and sense the beginning of interstellar space. Although Voyager 1 can still feel some of the sun's mag-

netic and charged particle influence, it is bathed in the material ejected millions of years ago by nearby giant stars.

As it heads away from home, Voyager 1 is rising above the ecliptic plane at an angle of about 35 degrees at a rate of about 340 million miles (540 million kilometers) a year. Voyager 2 is also headed out of the sun's magnetic influence, diving below the ecliptic plane at an angle of about 48 degrees and a speed of about 295 million miles (475 million kilometers) a year.

Both spacecraft will continue to explore ultraviolet sources among the stars, and the fields and particles instruments aboard the Voyagers will continue to explore the boundary between the sun's influence and interstellar space. The Voyagers are expected to return valuable data for at least another eight years. Communications will be maintained until the Voyagers' radioactive power sources can no longer supply enough electrical energy to power critical subsystems.

The cost of the Voyager 1 and 2 missions — including launch, mission operations and the spacecraft's nuclear batteries (provided by the Department of Energy) — is about \$988 million through September 2013.

## Operations

Voyagers 1 and 2 are identical spacecraft. Each was launched with instruments to conduct 10 different investigations. The instruments included television cameras, infrared and ultraviolet sensors, magnetometers, plasma detectors, and cosmic-ray and charged-particle sensors. Four of these instrument suites — the cameras, photopolarimeter and infrared and ultraviolet sensors — operated from a scan platform that enabled them to be pointed with an accuracy better than one-tenth of a degree. In addition, the spacecraft radio was used to conduct investigations.

The Voyagers travel too far from the sun to use solar panels; instead, they were equipped with power sources called radioisotope thermoelectric generators (RTGs). These devices, used on other deep space missions, convert the heat produced from the natural radioactive decay of plutonium into electricity to power the spacecraft instruments, computers, radio and other systems.

The spacecraft are controlled and their data returned through the Deep Space Network (DSN), a global spacecraft tracking system operated by JPL for NASA. DSN antenna complexes are located in California's Mojave Desert; near Madrid, Spain; and in Tidbinbilla, near Canberra, Australia.

## Jupiter

Voyager 1 made its closest approach to Jupiter on March 5, 1979, and Voyager 2 followed with its closest approach occurring on July 9, 1979. The first spacecraft flew within 128,400 miles (206,700 kilometers) of the planet's cloud tops, and Voyager 2 came within 350,000 miles (570,000 kilometers).

Jupiter is the largest planet in the solar system, composed mainly of hydrogen and helium, with small amounts of methane, ammonia, water vapor, traces of other compounds and a core of melted rock and ice. Colorful latitudinal bands and atmospheric clouds and storms illustrate Jupiter's dynamic weather system. The planet completes one orbit of the sun each 11.8 years, and its day is 9 hours, 55 minutes.

Although astronomers had studied Jupiter through telescopes on Earth for centuries, scientists were surprised by many of the Voyager findings.

The Great Red Spot was revealed as a complex storm moving in a counterclockwise direction. An array of other smaller storms and eddies were found throughout the banded clouds.



Voyager visited eight of Jupiter's moons and discovered three. Discovery of active volcanism on the satellite Io was easily the greatest unexpected discovery at Jupiter. It was the first time active volcanoes had been seen on another body in the solar system. Together, the Voyagers observed the eruption of nine volcanoes on Io, and there is evidence that other eruptions occurred between the Voyager encounters.

Plumes from the volcanoes extend to more than 190 miles (300 kilometers) above the surface. The Voyagers observed material ejected at velocities up to a kilometer per second.

Io's volcanoes are apparently due to heating of the satellite by tidal pumping. Io is perturbed in its orbit by Europa and Ganymede, two other large satellites nearby, then pulled back again into its regular orbit by Jupiter. This tug-of-war results in tidal bulging as great as 330 feet (100 meters) on Io's surface, compared with typical tidal bulges on Earth of 3 feet (1 meter).

It appears that volcanism on Io affects the entire jovian system, in that it is the primary source of matter that pervades Jupiter's magnetosphere — the region of space surrounding the planet influenced by the jovian magnetic field. Sulfur, oxygen and sodium, apparently erupted by Io's many volcanoes and sputtered off the surface by impact of high-energy particles, were detected as far away as the outer edge of the magnetosphere millions of miles from the planet itself.

Europa displayed a large number of intersecting linear features in the low-resolution photos from Voyager 1. At first, scientists believed the features might be deep cracks, caused by crustal rifting or tectonic processes. The closer high-resolution photos from Voyager 2, however, left scientists puzzled: The features were so lacking in topographic relief that as one scientist described them, they "might have been painted on with a felt

marker." There is a possibility that Europa may be internally active due to tidal heating at a level one-tenth or less than that of Io. Europa is thought to have a thin crust (less than 18 miles or 30 kilometers thick) of water ice, possibly floating on a 30-mile-deep (50-kilometer-deep) ocean.

Ganymede turned out to be the largest moon in the solar system, with a diameter measuring 3,280 miles (5,276 kilometers). It showed two distinct types of terrain — cratered and grooved — suggesting to scientists that Ganymede's entire icy crust has been under tension from global tectonic processes.

Callisto has a very old, heavily cratered crust showing remnant rings of enormous impact craters. The largest craters have apparently been erased by the flow of the icy crust over geologic time. Almost no topographic relief is apparent in the ghost remnants of the immense impact basins, identifiable only by their light color and the surrounding subdued rings of concentric ridges.

A faint, dusty ring of material was found around Jupiter. Its outer edge is 80,000 miles (129,000 kilometers) from the center of the planet, and it extends inward about 18,000 miles (30,000 kilometers).

Two new, small satellites, Adrastea and Metis, were found orbiting just outside the ring. A third new satellite, Thebe, was discovered between the orbits of Amalthea and Io.

Jupiter's rings and moons exist within an intense radiation belt of electrons and ions trapped in the planet's magnetic field. These particles and fields comprise the jovian magnetosphere, or magnetic environment, which extends three to seven million kilometers toward the sun, and stretches in a windssock shape at least as far as Saturn's orbit — a distance of 460 million miles (750 million kilometers).

As the magnetosphere rotates with Jupiter, it sweeps past Io and strips away about 1 ton (1,000 kilograms) of material per second. The material forms a torus, a doughnut-shaped cloud of ions that glow in ultraviolet wavelengths. The torus's heavy ions migrate outward, and their pressure inflates the jovian magnetosphere to more than twice its expected size. Some of the more energetic sulfur and oxygen ions fall along the magnetic field into the planet's atmosphere, resulting in auroras.

Io acts as an electrical generator as it moves through Jupiter's magnetic field, developing 400,000 volts across its diameter and generating an electric current of 3 million amperes that flows along the magnetic field to the planet's ionosphere.

## Saturn

The Voyager 1 and 2 Saturn flybys occurred nine months apart, with the closest approaches falling on November 12 and August 25, 1981. Voyager 1 flew within 40,000 miles (64,200 kilometers) of the cloud tops, while Voyager 2 came within 26,000 miles (41,000 kilometers).

Saturn is the second largest planet in the solar system and is distinguished by its complex, glittering ring system. It takes 29.5 Earth years to complete one orbit of the sun, and its day was clocked at 10 hours, 39 minutes. Like Jupiter, Saturn is mostly hydrogen and helium. Its hazy yellow hue was found to

be marked by broad atmospheric banding similar to but much fainter than that found on Jupiter. Close scrutiny by Voyager's imaging systems revealed long-lived ovals and other atmospheric features generally smaller than those on Jupiter.

Perhaps the greatest surprises and the most puzzles were found by the Voyagers in Saturn's rings. It is thought that the rings formed from larger moons that were shattered by impacts of comets and meteoroids. The resulting dust and boulder- to house-size particles have accumulated in a broad plane around the planet varying in density.



The two Voyager spacecraft took images of 17 of Saturn's moons, including four that they discovered. The irregular shapes of Saturn's eight smallest moons indicate that they, too, are fragments of larger bodies. Unexpected structure such as kinks and spokes were found in addition to thin rings and broad, diffuse rings not observed from Earth. Much of the elaborate structure of some of the rings is due to the gravitational effects of nearby satellites. This phenomenon is most obviously demonstrated by the relationship between the F-ring and two small moons that "shepherd" the ring material. The variation in the distances between the moons and the ring may explain the ring's kinked appearance. Shepherd moons were also found by Voyager 2 at Uranus.

Radial, spoke-like features in the broad B-ring were found by the Voyagers. The features are believed to be composed of fine, dust-size particles. The spokes were observed to form and dissipate in time-lapse images taken by the Voyagers. While electrostatic charging may create spokes by levitating dust particles above the ring, the exact cause of the formation of the spokes is not well understood.

Winds blow at extremely high speeds on Saturn — up to 1,100 mph (1,800 kilometers per hour). Their primarily easterly direction indicates that the winds are not confined to the top cloud layer, but must extend at least 1,200 miles (2,000 kilometers) downward into the atmosphere. The characteristic temperature of the atmosphere is minus 289 degrees Fahrenheit (95 kelvins).

Saturn holds a wide assortment of satellites in its orbit, ranging from Phoebe, a small moon that travels in a retrograde orbit and is probably a captured body, to Titan, the planet-sized moon with a thick nitrogen–methane atmosphere. Titan's surface temperature and pressure are minus 290 degrees Fahrenheit (94 kelvins) and 1.5 atmospheres. Photochemistry converts some atmospheric methane to other organic molecules, such as ethane, that is thought to accumulate in lakes or oceans. Other more complex hydrocarbons form the haze particles that eventually fall to the surface, coating it with a thick layer of organic matter. The chemistry in Titan's atmosphere may strongly resemble that which occurred on Earth before life evolved.

The most active surface of any moon seen in the Saturn system was that of Enceladus. The bright surface of this moon, marked by faults and valleys, showed evidence of tectonically induced change. Voyager 1 found the moon Mimas scarred with a crater so huge that the impact that caused it nearly broke the satellite apart.

Saturn's magnetic field is smaller than Jupiter's, extending only 0.6 to 1 million miles (1 or 2 million kilometers). The axis of the field is almost perfectly aligned with the rotation axis of the planet.

## Uranus

In its first solo planetary flyby, Voyager 2 made its closest approach to Uranus on January 24, 1986, coming within 50,600 miles (81,500 kilometers) of the planet's cloud tops.

Uranus is the third largest planet in the solar system. It orbits the sun at a distance of about 1.7 billion miles (2.8 billion kilometers) and completes one orbit every 84 years. The length of a day on Uranus as measured by Voyager 2 is 17 hours, 14 minutes.

Uranus is distinguished by the fact that it is tipped on its side. Its unusual position is thought to be the result of a collision with a planet-sized body early in the solar system's history. Given its odd orientation, with its polar regions exposed to sunlight or darkness for long periods, scientists were not sure what to expect at Uranus.

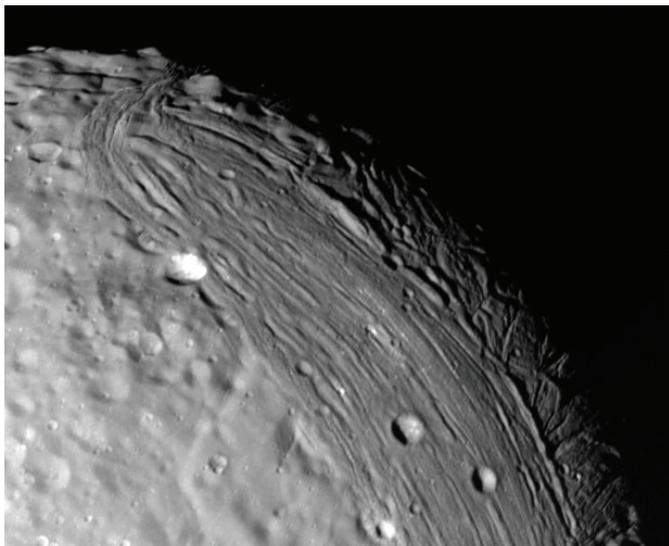
Voyager 2 found that one of the most striking influences of this sideways position is its effect on the tail of the magnetic field, which is itself tilted 60 degrees from the planet's axis of rotation. The magnetotail was shown to be twisted by the planet's rotation into a long corkscrew shape behind the planet.

The presence of a magnetic field at Uranus was not known until Voyager's arrival. The intensity of the field is roughly comparable to that of Earth's, though it varies much more from point to point because of its large offset from the center of Uranus. The peculiar orientation of the magnetic field suggests that the field is generated at an intermediate depth in the interior where the pressure is high enough for water to become electrically conducting.

Radiation belts at Uranus were found to be of an intensity similar to those at Saturn. The intensity of radiation within the belts is such that irradiation would quickly darken (within 100,000 years) any methane trapped in the icy surfaces of the inner moons and ring particles. This may have contributed to the darkened surfaces of the moons and ring particles, which are almost uniformly gray in color.

A high layer of haze was detected around the sunlit pole, which also was found to radiate large amounts of ultraviolet light, a phenomenon dubbed “dayglow.” The average temperature is about minus 350 degrees Fahrenheit (60 kelvins). Surprisingly, the illuminated and dark poles, and most of the planet, show nearly the same temperature at the cloud tops.

Voyager found 11 new moons at Uranus and visited 16. Most of the moons discovered by Voyager 2 are small, with the largest measuring about 90 miles (150 kilometers) in diameter.



The moon Miranda, innermost of the five large moons, was revealed to be one of the strangest bodies yet seen in the solar system. Detailed images from Voyager’s flyby of the moon showed huge fault canyons as deep as 12 miles (20 kilometers), terraced layers, and a mixture of old and young surfaces. One theory holds that Miranda may be a reaggregation of material from an earlier time when the moon was fractured by a violent impact.

The five large moons appear to be ice–rock conglomerates like the satellites of Saturn. Titania is marked by huge fault systems and canyons indicating some degree of geologic, probably tectonic, activity in its history. Ariel has the brightest and possibly youngest surface of all the Uranian moons and also appears to have undergone geologic activity that led to many fault valleys and what seem to be extensive flows of icy material. Little geologic activity has occurred on Umbriel or Oberon, judging by their old and dark surfaces.

All nine previously known rings were studied by the spacecraft and showed the Uranian rings to be distinctly different from those at Jupiter and Saturn. The ring system may be relatively young and did not form at the same time as Uranus.

Particles that make up the rings may be remnants of a moon that was broken by a high-velocity impact or torn up by gravitational effects.

## Neptune

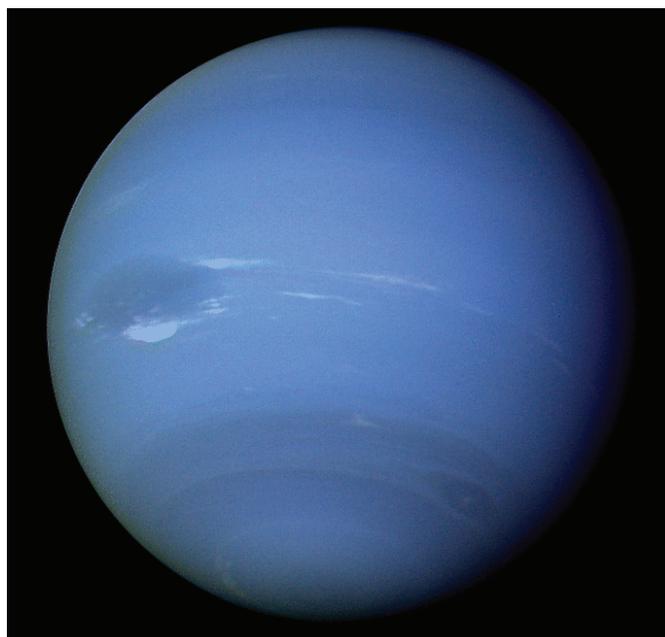
Voyager flew within 3,000 miles (5,000 kilometers) of Neptune on August 25, 1989. Neptune orbits the sun every 165 years. It is

the smallest of our solar system’s gas giants. The length of a Neptunian day has been determined to be 16 hours, 6.7 minutes.

Even though Neptune receives only three percent as much sunlight as Jupiter does, it is a dynamic planet and, surprisingly, showed several large, dark spots reminiscent of Jupiter’s hurricane-like storms. The largest spot, dubbed the Great Dark Spot, was about the size of Earth and similar to the Great Red Spot on Jupiter. A small, irregularly shaped, eastward-moving cloud was observed “scooting” around Neptune every 16 hours or so; this “scooter,” as Voyager scientists called it, could be a cloud plume rising above a deeper cloud deck.

Long, bright clouds, similar to cirrus clouds on Earth, were seen high in Neptune’s atmosphere. At low northern latitudes, Voyager captured images of cloud streaks casting their shadows on cloud decks below.

The strongest winds on any planet were measured on Neptune. Most of the winds there blow westward, or opposite to the rotation of the planet. Near the Great Dark Spot, winds blow up to 1,200 miles (2,000 kilometers) an hour.



The magnetic field of Neptune, like that of Uranus, turned out to be highly tilted — 47 degrees from the rotation axis and offset at least 0.55 radii (about 8,500 miles or 13,500 kilometers) from the physical center. Comparing the magnetic fields of the two planets, scientists think the extreme orientation may be characteristic of flows in the interiors of both Uranus and Neptune — and not the result in Uranus’s case of that planet’s sideways orientation, or of any possible field reversals at either planet. Voyager’s studies of radio waves caused by the magnetic field revealed the length of a Neptunian day. The spacecraft also detected auroras, but much weaker than those on Earth and other planets.

Voyager imaged eight of Neptune’s moons, discovering five of them. Triton, the largest of the moons of Neptune, was shown to be not only the most intriguing satellite of the Neptunian

system, but one of the most interesting in all the solar system. It shows evidence of a remarkable geologic history, and Voyager 2 images showed active geyser-like eruptions spewing invisible nitrogen gas and dark dust particles several miles (kilometers) into the tenuous atmosphere. Triton's relatively high density and retrograde orbit offer strong evidence that Triton is not an original member of Neptune's family but is a captured object. If that is the case, tidal heating could have melted Triton in its originally eccentric orbit, and the moon might even have been liquid for as long as one billion years after its capture by Neptune.

An extremely thin atmosphere extends about 500 miles (800 kilometers) above Triton's surface. Nitrogen ice particles may form thin clouds a few kilometers above the surface. The atmospheric pressure at the surface is about 14 micro-bars, 1/70,000th the surface pressure on Earth. The surface temperature is about minus 391 degrees Fahrenheit (38 kelvins), the coldest temperature of any body known in the solar system.

The new moons found at Neptune by Voyager are all small and remain close to Neptune's equatorial plane. Names for the new moons were selected from mythology's water deities by the International Astronomical Union. They are: Naiad, Thalassa, Despina, Galatea and Proteus.

Voyager 2 solved many of the questions scientists had about Neptune's rings. Searches for "ring arcs," or partial rings, showed that Neptune's rings actually are complete, but are so diffuse and the material in them so fine that they could not be fully resolved from Earth. From the outermost in, the rings have been designated Adams, Plateau, Le Verrier and Galle.

On February 14, 1990, Voyager 1 took the last pictures of the Voyager mission. Beyond the outermost planet in our solar system, at a distance of about 3.7 billion miles (6 billion kilometers), Voyager 1 turned its camera inward to snap a series of final images that became its parting valentine to the string of planets it called home.

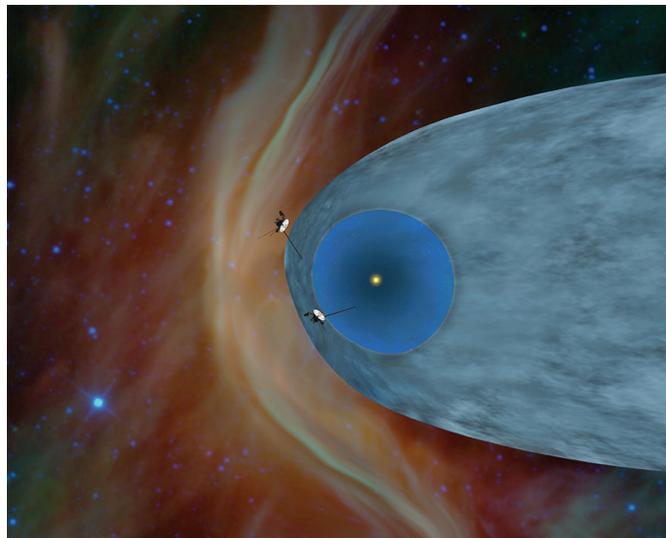
Mercury was too close to the sun to see, Mars showed only a thin crescent of sunlight, and Pluto was too dim, but Voyager was able to capture cameos of Neptune, Uranus, Saturn, Jupiter, Earth and Venus from its unique vantage point. These images, later arranged in a large-scale mosaic, make up the only family portrait of our planets arrayed about the sun.

It was an image from this set that inspired Carl Sagan, the Voyager imaging team member who had suggested taking this portrait, to call our home planet "a pale blue dot."

After that set of portraits, the cameras on Voyager 1 and 2 were switched off and the software controlling them removed from the spacecraft. There was very little for the cameras to see in the vast, dark emptiness of space. Mission managers needed to make space in the memory and conserve power for other instruments that would be able to detect the changes in the charged particles. It would be those changes that would describe what the far reaches of the solar system were like. This milestone marked the end of the Grand Tour mission and the beginning of Voyager's Interstellar Mission.

## Interstellar Mission

During its Interstellar Mission, the Voyagers have cruised gracefully in the solar wind. The solar wind is composed of electrically charged atomic particles — primarily ionized hydrogen — that stream outward from the sun. The interstellar medium restricts the outward flow of the solar wind and confines it within a magnetic bubble called the heliosphere.



The spacecraft have focused on collecting data on the strength and orientation of the sun's magnetic field; the composition, direction and energy of the solar wind particles and interstellar cosmic rays; the strength of radio emissions that are thought to be originating beyond the heliopause, which is the boundary with interstellar space; and the distribution of hydrogen within the outer heliopause. In May 1993, scientists concluded that the plasma wave experiment was picking up radio emissions that originate beyond the heliopause, the first measurement of the distance from the sun to interstellar space.

Where the planets are, the solar wind travels at supersonic speeds, but the pressure from gas between the stars abruptly slows the solar wind at a shockwave the scientists call the termination shock. The exact location of the termination shock was one of the great unanswered questions in space physics.

Voyager 1 crossed the termination shock, the location where the solar wind starts to "feel" the presence of the interstellar medium, on December 16, 2004, when it was about 8.7 billion miles (14 billion kilometers) from the sun. Voyager 2 first crossed the termination shock on August 30, 2007, when it was 7.8 billion miles (13 billion kilometers) from the sun. Before the termination shock, the speed of the solar wind was about 700,000 mph (300 kilometers per second). After the shock, the speed of the solar wind dropped to about 400,000 mph (180 kilometers per second).

After crossing the shock, the Voyagers sent home data about the heated, turbulent outer layer of the heliosphere known as the heliosheath. In April 2010, Voyager began to see additional signs of closing in on the heliopause, the dividing line between

the heliosphere and interstellar matter. Data from the spacecraft's low-energy charged-particle instrument indicated that the solar wind's outward speed had slowed to zero. The spacecraft team commanded Voyager to execute the first "roll-and-hold" maneuvers since 1990. Data returned after these maneuvers confirmed that the wind had not changed directions. Instead, Voyager had reached a kind of cosmic doldrums where there was very little wind.

Then, in May 2012, Voyager 1's cosmic ray instrument began detecting yet another sign of approaching the heliopause. These were jumps in the abundance of high-energy particles that originate from interstellar space. Also that same month, the spacecraft began seeing sharp drops in the abundance of low-energy particles that originate from inside our heliosphere. By July 2012, the pace of change increased, and on Aug. 25, 2012, the inside particles finally disappeared and the outside particles hit their highest level to that point. It was a surprise to scientists that the magnetic field direction did not show the abrupt change in direction that they expected. So, at the time they first described the changes in December 2012, the scientists did not have enough evidence to say that Voyager 1 had entered interstellar space.

The Voyager science team needed data from the plasma environment, and in April 2013, the plasma wave instrument detected oscillations in plasma it had not detected in seven years. A series of solar storms in March 2012 had blasted solar material out towards interstellar space. Thirteen months later, this solar material reached Voyager 1's location and made the interstellar plasma ring like a bell as the solar material plowed through it. The scientists could tell it had the density expected of cold interstellar plasma. A re-examination of their data revealed an earlier, fainter set of tones from October to November 2012. Extrapolating back, they deduced that Voyager 1 first encountered this dense plasma at the same time the levels of the charged particles changed. Even though Voyager 1 continues to sense some influence from the sun's charged particles and magnetic field, the team was convinced that Voyager 1 was seeing interstellar plasma. The date of interstellar arrival was on, or around, Aug. 25, 2012.

Scientists don't know when Voyager 1 will reach the undisturbed part of interstellar space. They also are not sure when Voyager 2 will cross the heliopause, though they don't believe it will be very far behind. Note: The plasma instrument aboard Voyager 1 stopped working in 1980, right after its last planetary flyby. An identical instrument is carried aboard Voyager 2, and it is operational. Voyager 2's plasma instrument provides data on the temperature, density and speed of plasma.

Both spacecraft are currently collecting fields and particle data with the cosmic ray subsystem, the low-energy charged particle instrument, the magnetometer and the plasma wave subsystem. The ultraviolet instrument on Voyager 1 is the only experiment on either spacecraft's scan platform that is still sending back data, though heaters around it have been turned off and it is operating at temperatures below minus 110 degrees Fahrenheit (minus 79 degrees Celsius). The data the ultraviolet spectrometer is collecting don't help distinguish between the heliosphere and interstellar space.

Data from all the instruments are transmitted to Earth in real time, typically at 160 bits per second, and captured by 34- and 70-meter Deep Space Network stations. After data are transmitted to JPL, they are made available to the science teams located around the country for processing and analysis. Voyager mission controllers still talk to and/or receive data from the Voyagers every day. The signals are very dim now. The Voyager transmits signals at about 20 watts — the power of a refrigerator light bulb. By the time the signals get to Earth, their power has diminished to a fraction of a billion-billionth of a watt.

Flight controllers believe both spacecraft will continue to operate the fields and particles science instruments until about 2020. The ultraviolet instrument on Voyager 1 will be turned off to conserve power for the other instruments in 2014. Starting around 2020, spacecraft engineers will turn off the fields and particles instruments one by one to conserve limited power, with the last instrument expected to go off around 2025.

On February 17, 1998, Voyager 1 passed the Pioneer 10 spacecraft to become the most distant human-made object in space. On August 13, 2012, Voyager 2 became the longest-operating spacecraft, surpassing Pioneer 6, which launched on Dec. 16, 1965, and sent its last signal back to NASA's Deep Space Network on Dec. 8, 2000. Voyager 1 is the second-longest-operating spacecraft.

### **Project Team**

At JPL, the position of Voyager project manager has been held successively by H.M. "Bud" Schurmeier (1972–76), John Casani (1976–77), Robert Parks (1978–79), Raymond Heacock (1979–81), Esker Davis (1981–82), Richard Laeser (1982–86), Norman Haynes (1987–89), George Textor (1989–97), Ed Massey (1998 to 2010) and Suzanne Dodd (2010 to present). Edward C. Stone is the Voyager project scientist. The assistant project scientist for the Jupiter flyby was Arthur L. Lane, followed by Ellis D. Miner for the Saturn, Uranus and Neptune encounters.

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