National Aeronautics and Space Administration

NASAfacts

Voyager to the Outer Planets

The twin spacecraft Voyager 1 and Voyager 2 were launched by NASA in separate months in the summer of 1977 from Cape Canaveral, Florida. As originally designed, the Voyagers were to conduct closeup studies of Jupiter and Saturn, Saturn's rings, and the larger moons of the two planets.

To accomplish their two-planet mission, the spacecraft were built to last five years. 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 the Jet Propulsion Laboratory in Pasadena, California.

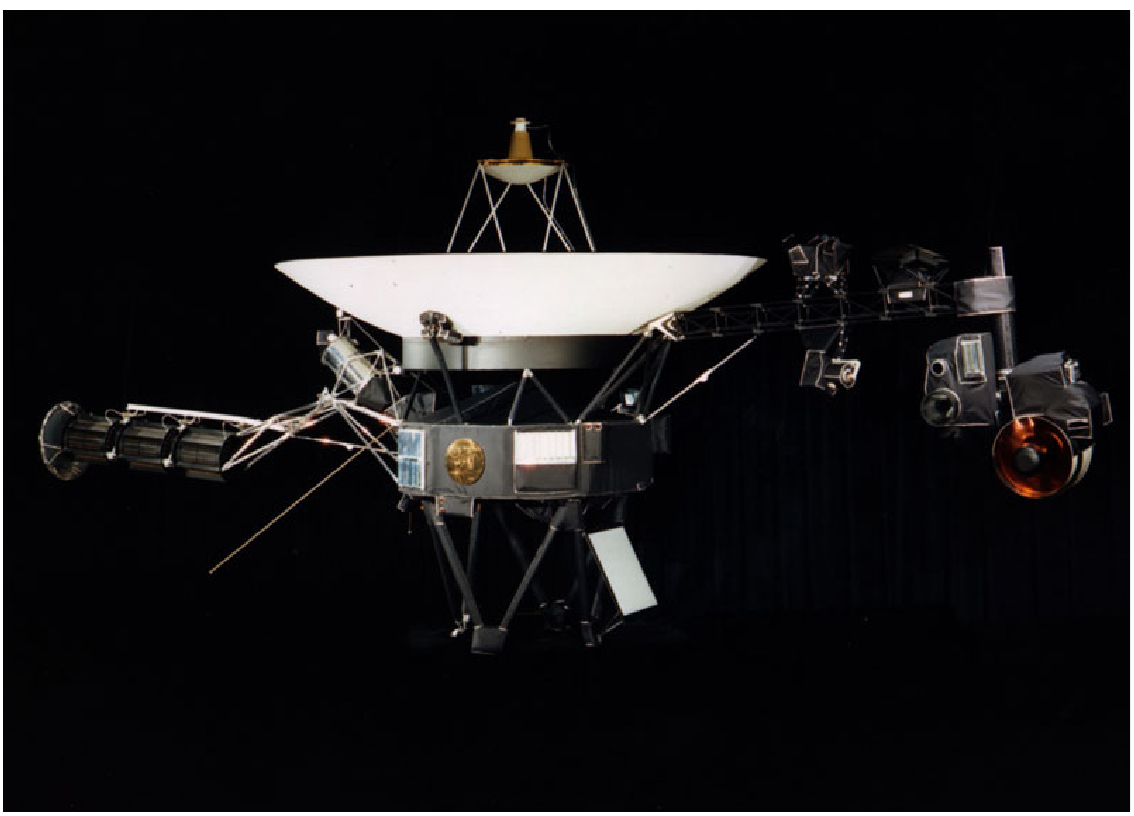
As the spacecraft flew across the solar system, remote-control reprogramming was used to endow the Voyagers with greater capabilities than they possessed when they left the Earth. Their two-planet mission became four. Their five-year lifetimes stretched to 12 and more.

Eventually, between them, Voyager 1 and 2 would explore all the 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 having doubled their already ambitious itineraries, the Voyagers returned to Earth information over the years that has revolutionized the science of planetary astronomy, helping to resolve key questions while raising intriguing new ones about the origin and evolution of the planets in our solar system.

Mission Concept

The Voyager mission was designed to take advantage of a rare geometric arrangement of the outer planets in the late 1970s and the 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 can be 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, Florida, Voyager 2 was launched first, on August 20, 1977; Voyager 1 was launched on a faster, shorter trajectory on September 5, 1977. 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. Voyager 2 was aimed to fly by Saturn at a point that would automatically send the spacecraft in the direction of Uranus.

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. Voyager 1, meanwhile, continues to press outward, conducting studies of interplanetary space. Eventually, its instruments may be the first of any spacecraft to sense the heliopause -- the boundary between the end of the sun's magnetic influence and the beginning of interstellar space.

Following Voyager 2's closest approach to Neptune on August 25, 1989, the spacecraft flew southward, below the ecliptic plane and onto a course that will take it, too, to interstellar space. Reflecting the Voyagers' new transplanetary destinations, the project is now known as the Voyager Interstellar Mission.

Voyager 1 is now leaving the solar system, rising above the ecliptic plane at an angle of about 35 degrees at a rate of about 520 million kilometers (about 320 million miles) a year. Voyager 2 is also headed out of the solar system, diving below the ecliptic plane at an angle of about 48 degrees and a rate of about 470 million kilometers (about 290 million miles) 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 search for the boundary between the sun's influence and interstellar space. The Voyagers are expected to return valuable data for at least another decade. 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 from launch through the Neptune encounter and the spacecraft's nuclear batteries (provided by the Department of Energy) -- was $865 million. The cost to operate the mission for the 18 years since the Neptune flyby and up through the end of fiscal year 2007 has been an additional $120 million.

Operations

Voyagers 1 and 2 are identical spacecraft. Each is equipped with instruments to conduct 10 different experiments. The instruments include television cameras, infrared and ultraviolet sensors, magnetometers, plasma detectors, and cosmic-ray and charged-particle sensors. In addition, the spacecraft radio is used to conduct experiments.

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 206,700 kilometers (128,400 miles) of the planet's cloud tops, and Voyager 2 came within 570,000 kilometers (350,000 miles).

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. As of fall 2007, the giant planet is known to possess 62 moons. 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.

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 300 kilometers (190 miles) 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 100 meters (330 feet) on Io's surface, compared with typical tidal bulges on Earth of one meter (three feet).

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 30 kilometers or 18 miles thick) of water ice, possibly floating on a 50-kilometer-deep (30-mile) ocean.

Ganymede turned out to be the largest moon in the solar system, with a diameter measuring 5,276 kilometers (3,280 miles). 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 129,000 kilometers (80,000 miles) from the center of the planet, and it extends inward about 30,000 kilometers (18,000 miles).

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 windsock shape at least as far as Saturn's orbit -- a distance of 750 million kilometers (460 million miles).

As the magnetosphere rotates with Jupiter, it sweeps past Io and strips away about 1,000 kilograms (one ton) of material per second. The material forms a torus, a doughnut-shaped cloud of ions that glow in the ultraviolet. 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 64,200 kilometers (40,000 miles) of the cloud tops, while Voyager 2 came within 41,000 kilometers (26,000 miles).

Saturn is the second largest planet in the solar system. It takes 29.5 Earth years to complete one orbit of the sun, and its day was clocked at 10 hours, 39 minutes. Saturn is known to have 60 moons (as of fall 2007) and a complex ring system. 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 irregular shapes of Saturn's eight smallest moons indicates 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 separation of the moons from the ring may the ring's kinked appearance. Shepherding 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 1,800 kilometers per hour (1,100 miles per hour). Their primarily easterly direction indicates that the winds are not confined to the top cloud layer but must extend at least 2,000 kilometers (1,200 miles) downward into the atmosphere. The characteristic temperature of the atmosphere is 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 asteroid, to Titan, the planet-sized moon with a thick nitrogen-methane atmosphere. Titan's surface temperature and pressure are 94 kelvins (-292 Fahrenheit) 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 one or two 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 81,500 kilometers (50,600 miles) 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 2.8 billion kilometers (1.7 billion miles) 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 60 kelvins (-350 degrees Fahrenheit). Surprisingly, the illuminated and dark poles, and most of the planet, show nearly the same temperature at the cloud tops.

Voyager found 10 new moons, bringing the total number then to 15. (As of fall 2007, Uranus is known to possess 27 moons.) Most of the moons discovered by voyager 2 are small, with the largest measuring about 150 kilometers (about 90 miles) 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 20 kilometers (12 miles), terraced layers, and a mixture of old and young surfaces. One theory holds that Miranda may be a reaggregration of material from an earlier time when the moon was fractured by an 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 5,000 kilometers (3,000 miles) of Neptune on August 25, 1989. Neptune orbits the sun every 165 years. It is the smallest of our solar system's gas giants. As of fall 2007, Neptune is known to have 13 moons, six of which were found by Voyager. 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, is about the size of Earth and is 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 2,000 kilometers (1,200 miles) 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 13,500 kilometers or 8,500 miles) 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.

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 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 800 kilometer (500 miles) 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 microbars, 1/70,000th the surface pressure on Earth. The surface temperature is about 38 kelvins (-391 degrees Fahrenheit), 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, Larissa, 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.

Interstellar Mission

The spacecraft are continuing to return data about interplanetary space and some of our stellar neighbors near the edges of the Milky Way.

As the Voyagers cruise gracefully in the solar wind, their fields, particles and waves instruments are studying the space around them. The spacecraft are collecting data on the strength and orientation of the sun's magnetic field; the composition, direction and energy specta of the solar wind particles and interstellar cosmic rays; the strength of radio emissions that are thought to be originating at the heliopause, beyond which is 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 at the heliopause -- the outer edge of our solar system.

The heliopause is the outermost boundary of the solar wind, where the interstellar medium restricts the outward flow of the solar wind and confines it within a magnetic bubble called the heliosphere. The solar wind is made up of electrically charged atomic particles, composed primarily of ionized hydrogen, that stream outward from the sun. But the spacecraft would first encounter the termination shock. The termination shock is where the solar wind, a thin stream of electrically charged gas blowing continuously outward from the sun, is slowed by pressure from gas between the stars. At the termination shock, the solar wind slows abruptly from its average speed of 300 to 700 kilometers per second (700,000 to 1.5 million miles per hour), and becomes denser and hotter. Exactly where the termination shock is has been one of the great unanswered questions in space physics.

On December 16, 2004, Voyager 1 crossed the termination shock entering the solar system's final frontier. The spacecraft then entered the heliosheath, the region beyond the termination shock at 8.7 billion miles from the sun. It has since been in the heliosheath. Voyager 1 is expected to pass beyond the heliopause into interstellar space in eight to 10 years. Voyager 2 has now followed its twin into the final frontier.

The cameras on the spacecraft have been turned off, and the ultraviolet instrument on Voyager 1 is the only experiment on the scan platform that is still functioning. Voyager scientists expect to continue to receive data from the ultraviolet spectrometers at least until the year 2009. At that time, there might not be enough electrical power for the heaters to keep the ultraviolet instrument warm enough to operate.

Yet there are several other fields and particle instruments that can continue to send back data as long as the spacecraft stay alive. They include: the cosmic ray subsystem, the low-energy charge particle instrument, the magnetometer, the plasma subsystem and the plasma wave subsystem. However, the plasma instrument sensitivity on Voyager 1 is severely degraded, limiting the science value of the data. Data from all the instruments are transmitted to Earth in real time, at 160 bits per second, and captured by 34- and 70-meter Deep Space Network stations. After transmission of the data to JPL, it is made available in electronic files to the science teams located around the country for their processing and analysis.

Flight controllers believe both spacecraft will continue to operate and send back valuable data until at least the year 2020. On February 17, 1998, Voyager 1 passed the Pioneer 10 spacecraft to become the most distant human-made object in space.

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) and Ed Massey (1998 to present). Dr. Edward C. Stone is the Voyager project scientist. The assistant project scientist for the Jupiter flyby was Dr. Arthur L. Lane, followed by Dr. Ellis D. Miner for the Saturn, Uranus and Neptune encounters.

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