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Voyages to Saturn

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Foreword

The Voyager spacecraft were outstanding successes in their serial flybys of Saturn—returning far more new information than had been collected in three centuries of Earth observation. It would be well to remember that these are risky ventures, involving intricate mechanisms dispatched hundreds of millions of miles to perform subtle and delicate measurements, traversing immense distances of cold, dark, airless space, and surviving unexplored fields of particles and magnetic force.

That we can confidently plan and execute such ventures is testimony to the power of high technology well and artfully employed. It indicates that the academic community, the Federal Government, and American industry can work together in these landmark enterprises with a comity (and mutual advantage) not always found in ordinary associations.

December 1981

James M. Beggs
Administrator
National Aeronautics and Space Administration

Pioneer to Saturn

The space age dawned in 1957 with the launch of Sputnik 1, the first artificial satellite, followed within five years by many more spacecraft, including a flyby of Venus by the first interplanetary spacecraft, Mariner 2. Additional United States Mariner missions to the planets followed, with exploratory visits to Mars in 1964 and 1969, returns to Venus in 1965 and 1974, a first reconnaissance of Mercury in 1974, and an extremely successful Mars orbiter in 1971. In the same period the USSR sent a dozen spacecraft to Mars and Venus and successfully landed instrumented probes on the surface of Venus. These missions, in addition to the extensive exploration of the Moon carried out in preparation for the Apollo landings, provided a revolutionary new perspective on our sister worlds in the inner solar system. But what of the giant gas planets, separated by immense distances, floating in the deep cold of the outer solar system? Could we reach them too? By the late 1960s, NASA scientists and engineers were determined to try.

Several barriers stood in the way of a successful exploration of the outer solar system. The most difficult to overcome was the vast distance which necessitated larger rockets and much more reliable, automatic spacecraft that could spend years unattended in space and still provide flawless operation as they reached a remote world. Other barriers included the difficulties of communicating over such vast distances and the lack of a satisfactory solar power source so far from the Sun. It was clear that a new generation of spacecraft employing fundamental advances in electronics, power sources, communications, and reliability would be required to reach to Jupiter, Saturn, and beyond.

Jupiter, the nearest of the giant planets, was a logical first target; Saturn and more distant planets at first seemed beyond our reach. Then, in the late 1960s, scientists began to find solutions that opened up the more distant reaches of the solar system. In any gravitational encounter between two bodies—a planet and a spacecraft, for instance—one will lose energy and the other will gain it. Why not aim a spacecraft to fly past Jupiter in just the right way to gain speed and receive a boost toward the next target, Saturn? In this way, the launch vehicle requirements and travel times to distant objects were greatly reduced. A launch at the time of the appropriate planetary configuration and careful navigation would ensure that the gravitational boost would be just right to provide the correct trajectory to the second target.

In the late 1970s, all the outer planets would lie in a rough alignment, inspiring mission planners to link several gravity-assisted encounters, so that a single spacecraft could explore three or four planets, gaining energy from each encounter to speed it on to its next target. This concept of a series of multiplanet flights was named the Outer Planets Grand Tour, and NASA hoped to initiate the missions for launch between 1977 and 1979.

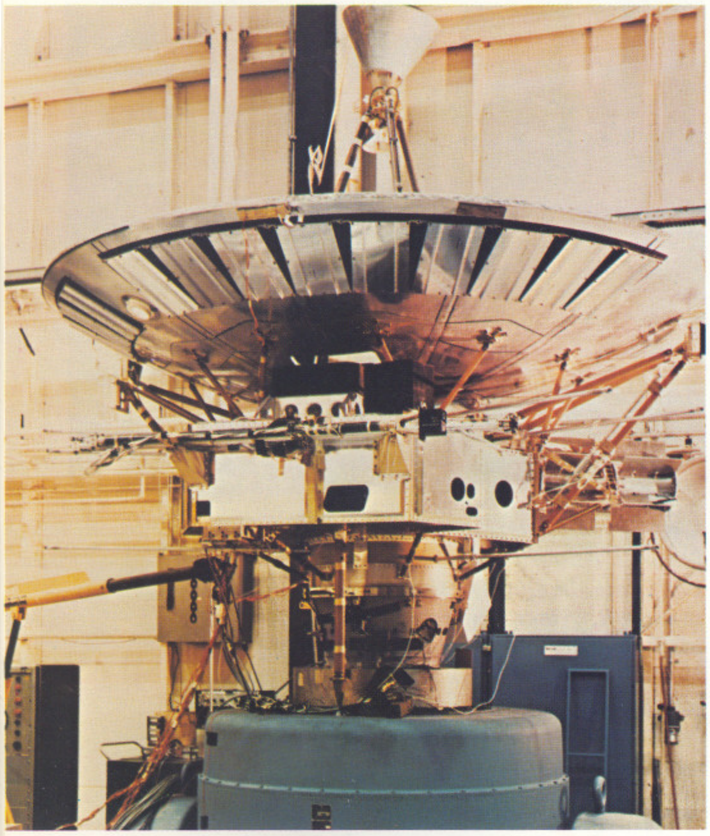
The essential first step in the Grand Tour was a flyby of Jupiter. In addition to the distance, which was much greater than had been dealt with in previous planetary missions, a spacecraft to Jupiter would encounter two other potentially serious problems: the asteroid belt and the Jovian magnetosphere. The asteroids are small planets that orbit the Sun between Mars and Jupiter; it was feared that this region of space might contain so much debris that a lethal impact would be likely for any spacecraft bound for the outer solar system. The Jovian magnetosphere, like that of Earth, contains energetic electrons, protons, and heavy ions trapped in the planet's magnetic field; calculations of the resulting radiation suggested that the delicate electronic parts of a spacecraft might be "cooked." The first step in any program of exploration beyond Mars was to assess these potential dangers. The Pioneer Project was created to carry out this pathfinding task.

The Pioneer Mission

The Pioneer Jupiter Mission began in 1969. Its objectives were to explore the interplanetary medium beyond Mars, to assess the hazards of the asteroid belt, and to explore the magnetosphere of Jupiter. At that time, no one imagined that Pioneer would also provide our first visit to Saturn, nearly twice as far from Earth as Jupiter.

The Pioneer Project was assigned by NASA to its Ames Research Center near San Francisco, with Charles F. Hall as Project Manager and magnetospheric physicist John H. Wolfe as Project Scientist. The spacecraft, designed for simplicity and reliability, was based on a series of successful Earth-orbiting probes. Unlike the Mariner spacecraft used for investigation of the inner planets, the Pioneers rotated several times per minute around an axis pointed toward Earth. In addition to providing stability, this arrangement ensured that the disk-shaped communications antenna remained aligned toward Earth. It was ideal for particles and fields instruments—those designed to measure the magnetic fields and charged particles in the immediate vicinity of the spacecraft. The spinning design allowed these instruments to point successively in many directions, so that they could accurately characterize the trajectories of the charged particles, moving with the magnetic fields in space. A spinning spacecraft does not, however, provide a good base for optical instruments, which must remain pointed toward a

The Pioneer missions were controlled from NASA's Ames Research Center near Palo Alto, California. In addition to its work on the Pioneer spacecraft, Ames has led in the NASA development of direct entry probes for the atmospheres of Venus and Jupiter and carries out major life sciences research. Ames is also one of the most important NASA centers for aeronautical research and development.



The two Pioneer spacecraft were designed and fabricated by TRW Systems Group at their Redondo Beach, California, facility. Each weighed about 260 kilograms and carried a set of sophisticated instruments for the scientific investigation of Jupiter and Saturn and of interplanetary space. Data systems on board controlled the instrumentation, received and processed commands, and transmitted information across the vast distance to Earth.

distant target. Pioneer carried three optical instruments, but these were of secondary importance.

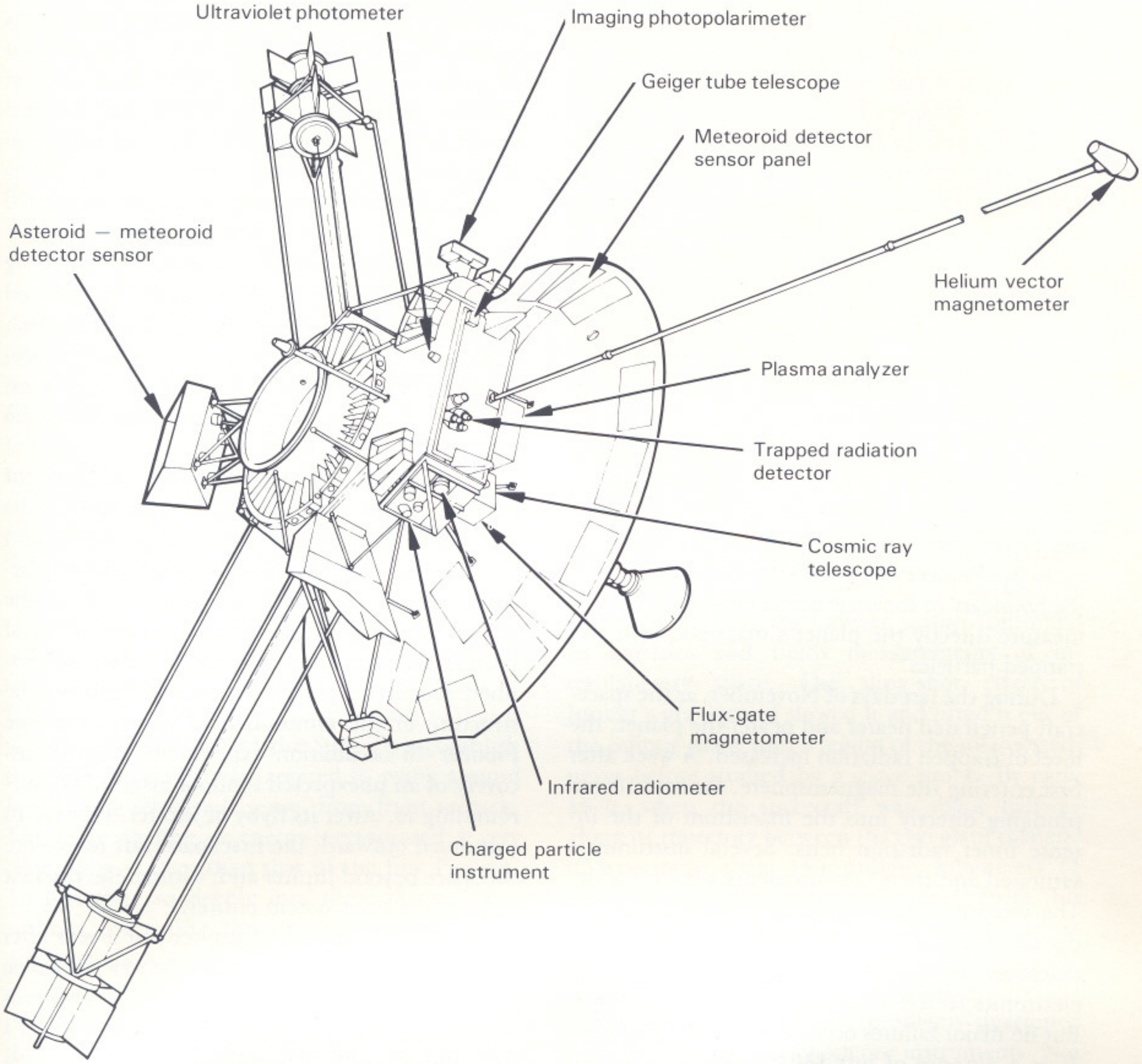
Each Pioneer spacecraft—designated after launch as Pioneers 10 and 11—had a mass of 258 kilograms and was about the size of a large kitchen range. Since sunlight would be so weak in the outer solar system, the spacecraft carried their own specially developed power sources—radioisotope thermoelectric generators (RTGs) that provided 140 watts of power. The launch vehicle was an Atlas-Centaur rocket equipped with an additional solid-propellant third stage. This powerful combination could accelerate the spacecraft to a speed of more than 50 000 kilometers per hour, the highest speed ever reached by an interplanetary spacecraft.

Control and communication over distances of nearly a billion kilometers constituted major challenges for the Pioneer Jupiter team. The light travel time imposed an inevitable lag between events at the spacecraft and receipt of a radio signal on Earth. It was decided, however, not to undertake the difficult task of designing an autonomous spacecraft (as the later Voyagers would be), but to learn to operate with ground control in spite of the round-trip time lag of 90 minutes for Jupiter and nearly three hours for Saturn.

The same radio link that transmitted instructions from Earth-based controllers also carried the data from the spacecraft instruments back to the waiting scientists. The transmitter power was only 8 watts. The incredibly weak signals received on Earth were picked up by the giant 64-meter-diameter antennas of three NASA Deep Space Tracking Stations in California, Australia, and Spain, and were relayed from there to Ames Research Center. The weaker the signal, the more slowly the data must be transmitted to ensure the necessary data quality. From Jupiter, Pioneer transmitted at 2048 data bits per second, while from Saturn the rate was partly 512 and partly 1024 bits per second.

Equipment for eleven scientific investigations was carried on Pioneer, providing a 25-kilogram payload of instruments. These instruments were chosen competitively from proposals submitted to NASA in 1969 by scientists from universities, industry, NASA laboratories, and from abroad. Seven of the instruments selected measured particles and fields, two investigated meteoroidal debris near the spacecraft, three carried out remote sensing observations of Jupiter and its environment, and two made use of the spacecraft itself to carry out scientific investigations.

Less than three years after the start of the Pioneer Project, the first spacecraft was ready for launch from the Kennedy Space Center at Cape



Twelve instruments were carried on board the Pioneer Saturn spacecraft. Seven of these were designed to measure particles and fields, two recorded small particles, and three were remote sensing instruments designed to study Jupiter, Saturn, and their rings and satellites.

Canaveral, Florida. Pioneer 10 began its historic journey toward Jupiter on March 2, 1972. The second spacecraft was to wait more than a year before launch, so that the results from Pioneer 10 could be used in the selection of a trajectory for Pioneer 11's Jupiter flyby. This interval between the launches of the two spacecraft was to play a crucial role in the ultimate decision to send the second spacecraft on to Saturn. Pioneer 11 was finally launched on April 5, 1973, to begin its billion-kilometer, two-year flight to Jupiter.

Encounters With Jupiter

In July 1972 Pioneer 10 entered the asteroid belt, the first major supposed barrier to outer solar system exploration. To the relief of all, no danger in the small debris was detected, and the spacecraft emerged unscathed in February 1973. A year later, Pioneer 11 made an equally uneventful transit of the asteroid belt. The pathway to the outer solar system was open! The Pioneers were halfway to their goals, but there remained the major challenge of the potentially lethal magnetosphere of Jupiter.

On November 26, 1973, Pioneer 10 began its encounter with the giant planet. At a distance of 8.5 million kilometers—109 Jupiter radii (R_J)—the spacecraft sensed an abrupt change in its environment. It had reached the bow shock, the region where the supersonic solar wind of outward-flowing charged particles is suddenly slowed to subsonic speed by the impending barrier of the Jovian magnetosphere. The next day, at 96 R_J, Pioneer 10 crossed the magnetopause—the boundary of the magnetosphere—and began to measure directly the planet's magnetic field and trapped particles.

During the last days of November, as the spacecraft penetrated nearer and nearer the planet, the level of trapped radiation increased. A week after first entering the magnetosphere, Pioneer 10 was plunging directly into the maelstrom of the intense inner radiation belts. Several instruments saturated and their measurements went off scale. The intense blast of x-rays and gamma rays induced by collisions with energetic charged particles resulted in false computer commands, as the electronics teetered near the edge of breakdown. But no major failures occurred, and on December 3, at a distance of just 130 000 kilometers from the cloud tops, Pioneer 10 passed its closest approach to Jupiter and began its return toward calmer waters. The little spacecraft had passed its most severe test with flying colors, laying the foundation on which all subsequent missions to Jupiter would be built.

At the same time that the particles and fields instruments on Pioneer 10 were analyzing the magnetosphere, the three optical instruments were observing Jupiter and its satellites. The photopolarimeter, operating as a line-scan camera, built up photographs of the planet showing individual features as small as 500 kilometers across and providing new insight into the complex motions of the Jovian atmosphere. An infrared instrument measured the thermal output of Jupiter, verifying that the planet had an internal heat source of some 10^{17} watts (a hundred billion megawatts) in addition to the energy provided by absorbed sunlight. This instrument also measured helium in Jupiter's atmosphere. The ultraviolet photometer mapped glows, presumably arising from hydrogen gas, coming from Jupiter and from a large region near its innermost large satellite, Io. Analysis of the spacecraft trajectory provided information on the fluid interior of Jupiter, and the magnetometer data mapped out the planet's magnetic field.

The trajectory of Pioneer 10 was chosen not only to measure the intense inner radiation belts but also to probe the atmospheres of Jupiter and Io. As seen from Earth, the spacecraft passed behind, or was occulted by, each object. The changes induced in the radio signal as a result of passing through the ionosphere or neutral atmosphere provided a powerful means of deducing the structure of the atmosphere. One result of the Pioneer 10 occultation experiment was the discovery of an unexpected tenuous atmosphere surrounding Io. After its flyby of Jupiter, Pioneer 10 continued outward, the first spacecraft to explore the space beyond Jupiter and, ultimately, the first to leave the solar system entirely.

Pioneer 11 approached Jupiter just a year after Pioneer 10. In the meantime, the Pioneer 10 data on the magnetosphere had been analyzed, and project officials felt confident that they could select a new and in many ways more demanding trajectory for Pioneer 11. It had been calculated that, if Pioneer 11 flew close enough to Jupiter, its orbit could be bent back on itself; in this way the spacecraft could be redirected toward Saturn, on nearly the other side of the solar system. This was not an ideal way to reach Saturn—indeed, the alignment could hardly have been worse—but it allowed the possibility that Pioneer 11 would be the first spacecraft to reach the ringed planet. In spite of the risks, the Pioneer engineers and scientists had confidence that their sturdy craft could meet this challenge, which greatly exceeded the original objectives of the Pioneer program.

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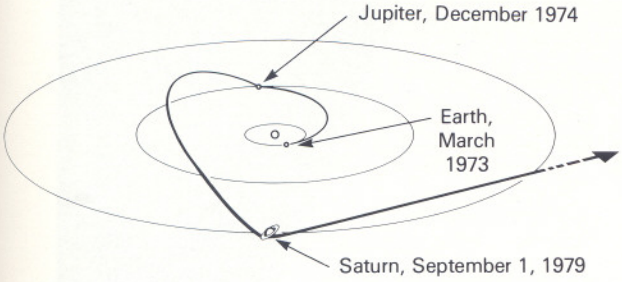


The trajectory of Pioneer Saturn required a two-billion-kilometer trip across the solar system. Following its launch in 1973, this spacecraft traveled outward to Jupiter, arriving late in 1974. Following a retrograde flyby of Jupiter, the spacecraft traveled nearly across the solar system to its historic encounter with Saturn in 1979. After the Saturn encounter, the Pioneer spacecraft continued to move outward, ultimately to escape entirely from the Sun's gravity.

Because Saturn was on the other side of the Sun from Jupiter, it was necessary to use the gravity of Jupiter to slow the Pioneer 11 spacecraft so that it would drop back toward the Sun. To accomplish this, the spacecraft was targeted to swing around Jupiter in a retrograde sense, from front to back. The large change in energy necessitated a very close flyby—closer than that of the first Pioneer. To penetrate so deeply into the radiation belts without overtaxing the spacecraft, the mission directors chose a path that cut across the Jovian equatorial plane at a high angle. Since most of the magnetospheric energetic particles were near the equator, this oblique trajectory actually produced a smaller total radiation dose, even though the peak intensity exceeded that experienced by Pioneer 10. This high-inclination orbit also provided a glimpse of the polar regions of Jupiter and a sampling of the magnetospheric structure at high latitudes.

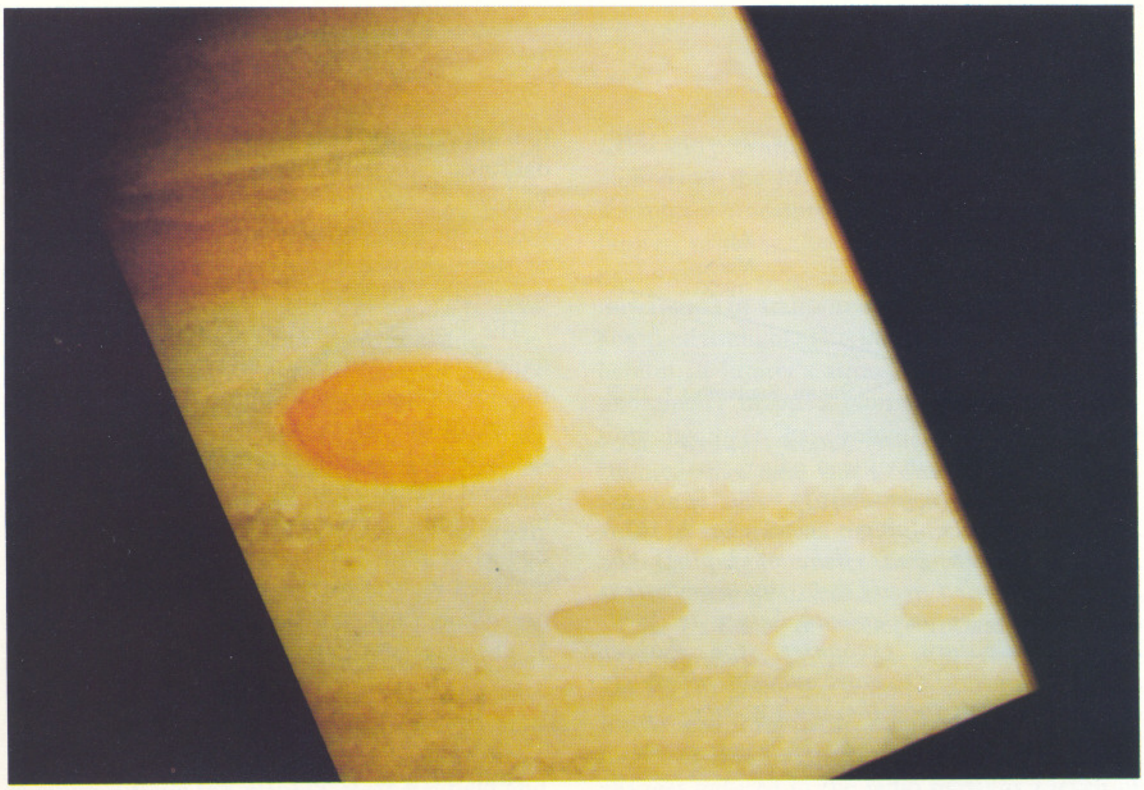
On November 26, 1974, Pioneer 11 crossed the Jovian bow shock. Closest approach to Jupiter, on December 2, was only 43 000 kilometers above the cloud tops. Ironically, the most serious threat to the success of the encounter developed not in space, but on Earth, where a strike by diesel generator operators at the Australian tracking station almost caused the loss of six hours of unique data near closest approach. Like its predecessor, Pioneer 11 suffered radiation-induced problems during the hours of strongest exposure, but none of these resulted in permanent damage to the spacecraft or its scientific instruments.

The Pioneer 11 pictures of Jupiter were even more detailed than those of Pioneer 10. Studies of the Jovian polar areas provided new data on regions of the planet poorly seen from either the Earth or the later Voyager encounters, and a great deal was learned about the complex physics of the magnetosphere. Following the successful completion of its Jupiter investigations, Pioneer 11 was renamed Pioneer Saturn by NASA, and the Pioneer Project was formally extended to include a Saturn encounter five years later, in 1979.

Targeting at Saturn

From 1974 to 1979 Pioneer Saturn continued its particles and fields measurements of interplanetary space. The sling-shot effect of Jupiter's gravity had slowed it and lifted it out of the ecliptic plane into a region of the solar system never before studied by a space probe. By early 1976, when the spacecraft was about halfway along its trajectory between the two giant planets, it was more than 150 million kilometers (1 astronomical unit) north of the Sun. From this unique perspective, Pioneer discovered properties of the solar magnetic field that could not be detected from the plane of the planets.

During the long flight, problems developed with two of the Pioneer science instruments. Not long after the Jupiter encounter, occasional spurious electronic command signals began to appear, which, after several months of detective work, were attributed to problems in the circuits of one of the meteoroid-detection instruments. Since the damage could not be repaired, it was necessary to turn off the instrument. A more serious problem was the loss of the plasma detector. As part of the test sequence that eventually identified the source of the spurious commands, the plasma instrument was switched off and left in that mode for several days, allowing it to cool—by too much, as it turned out. When the



One of the best Pioneer images of Jupiter was obtained at a range of 545 000 kilometers by Pioneer 11. Structure within the Great Red Spot and the surrounding belts and zones can be seen. There was less turbulent cloud activity around the Spot at the times of the Pioneer flybys than was seen five years later by the Voyager cameras.

command to restart was sent, the plasma instrument did not respond. Further efforts to restore this important fields and particles detector were made, but to no effect.

The Jupiter flyby had aimed Pioneer in the general direction of Saturn, but several times during the long years of flight across the solar system it was necessary to use the onboard rocket to make small trajectory corrections. The nominal aimpoint was to one side of the planet and rings. By the end of 1977 it was necessary to decide exactly what sort of flyby would be the most scientifically productive. Several options were considered, including a plunge directly through the Cassini Division, but in the end two targeting choices came to the forefront, each with its own rationale and advocates.

The "inside" option provided the closest possible flyby of Saturn, and hence the greatest penetration of the magnetosphere. The aimpoint would be about midway between the inner edge of the C Ring and the cloud tops. The problem with this trajectory was the danger of the ring plane crossing which would occur within the faint D Ring. Various estimates of the expected particle density in the D Ring suggested a low probability of spacecraft survival.

The greatest danger to the spacecraft would come from ring particles in the size range from about a millimeter to a centimeter—a grain of sand to a pea. At about 30 kilometers per second, the speed at which a collision with the spacecraft would take place, these particles would blast clear through the spacecraft structure; even one such impact could be lethal. Much smaller particles could not penetrate the skin of the spacecraft; if they were much larger they would be so widely spaced that there probably would not be any hits at all. Unfortunately, no one knew the typical size of the particles in the D Ring, so estimates of the chances of spacecraft survival ranged from less than 1 percent to greater than 99 percent.

The "outside" targeting option for Pioneer was at a point well outside the visible rings, at a distance of 2.9 Saturn radii (R_S) from the center of the planet. In addition to being considered much safer, this location was desirable because it was exactly the distance from Saturn at which Voyager 2 would have to cross the rings in 1981 if it were to continue to Uranus.

The question of which option would produce the most useful scientific results was complex. Either trajectory could tell something about the density of ring particles if it resulted in a catastrophic death of the spacecraft, but that seemed a high price to pay. The inside option could yield the most exciting results, but the advantage would be lost if an untimely end at ring plane crossing terminated the mission. After considerable debate, the twelve Pioneer Saturn Principal Investigators voted 11 to 1 for the inside option, arguing for the importance of this unique opportunity to make measurements close to the planet. There was a kind of bravura spirit that imbued this group who had been working together for more than a decade: If little Pioneer had survived so far against all the odds, why not go for broke? It just might make it through the D Ring, and, if not, at least the mission would end on a dramatic note.

Other considerations, however, favored the more conservative course. The primary scientific arguments for the outside option were based on the importance of the survival of the spacecraft, so that it could complete its investigations of Saturn and Titan (which would be missed entirely if the spacecraft were lost on ring plane crossing) and continue to measure interplanetary space beyond Saturn. In addition, Voyager Project officials argued for the importance of Pioneer's pathfinding role. They were worried about targeting Voyager 2 so close to the rings, and they felt that if any spacecraft were to be risked on this venture, it should be the Pioneer, already beyond its nominal lifetime, and not the more capable Voyager in the midst of its mission.

The final targeting decision was made in May 1978 by Tom Young, then the Director of Planetary Programs at NASA Headquarters. Overruling the recommendation of the Pioneer Principal Investigators, he selected the outside option as likely to provide a greater total scientific return from both Pioneer and Voyager. Thus Pioneer became, in a sense, the pathfinder to Uranus as well as to Jupiter and Saturn.

The final burn of the small rockets that adjusted the trajectory was made in July 1978. The target date for encounter was set for September 1, 1979; without this change in the flight path, the encounter would have taken place several days later, when radio interference from the Sun, nearby in the sky at this time of year, would have created problems for the spacecraft telemetry signal. The exact time of day was selected to permit redundant Earth coverage by the Deep Space Network stations in Australia and Spain during the most critical part of the encounter.

Early in 1979 Pioneer was well north of the ecliptic but descending rapidly toward Saturn, still more than 200 million kilometers away. At this part of Saturn's orbit, the rings were only slightly inclined to the Sun; a year later, they would appear exactly edge-on. The sunlight provided oblique illumination (at a 2 degree angle at encounter) of the southern face of the rings, while the spacecraft saw the northern face at an inclination of 6 degrees—a unique (if somewhat confusing) perspective that added considerably to the importance of the Pioneer images.

In the meantime, another fortunate event took place: the resurrection of the plasma instrument, which had been inoperative since April 1975. During October and November 1977, a special series of commands had been sent to Pioneer to try to overcome the damaged electronic switching circuits that were believed to be the source of the failure—the remote equivalent of kicking a recalcitrant machine. On December 3, 1977, the plasma instrument responded and returned to normal operation, ready to do its part in the first exploration of the magnetosphere of Saturn.

Encounter With Saturn

As the Pioneer spacecraft neared Saturn in August 1979, the primary scientific interest focused on the magnetic field and associated magnetosphere of the planet. Although there was some evidence of long-wave radio bursts detected near

Earth, the very existence of a magnetosphere was open to doubt. The question was not whether Saturn had a magnetic field—most investigators felt sure it did—but whether this field trapped many charged atomic particles. It seemed certain that charged particles entering the inner magnetosphere would collide with the rings and be eliminated. There might be interesting consequences of such collisions, such as the production of a tenuous atmosphere of water vapor from the icy material of the rings. If the faint but wide E Ring were real, the collisional sweeping up of magnetospheric particles could extend over most of the magnetosphere.

Another mystery concerned the interaction of Titan with the magnetosphere of Saturn. Here might be the unique situation of a satellite with a large atmosphere orbiting within a magnetosphere; atoms escaping from the atmosphere could possibly constitute a major source of charged particles, like the sulfur dioxide molecules from volcanoes on the Jovian satellite Io. Investigators wondered how strong the magnetic field was, and how large the magnetosphere might be. If it did not extend to the orbit of Titan, the situation would be very different. Theorists had developed a variety of alternative models for the magnetosphere of Saturn depending on whether Titan was inside or outside.

The Jovian magnetosphere had extended to about 100 R_J during the Pioneer encounters, but it had been compressed to only about 50 R_J during the Voyager encounters, which took place in a period of high solar wind pressure. Before Pioneer, the best guess was that Saturn's magnetosphere might be about half as large—perhaps in the range of 25–50 R_S. The radius of the orbit of Titan is 20 R_S. If the larger value were the true one, the Pioneer spacecraft would reach the bow shock on August 30, two days before encounter. Scientists anxiously watched the data from the particles and fields instruments all night and into the morning of August 31. As additional experimentors and members of the press arrived, everyone asked if there had been any sign of the bow shock. Could it be that Saturn had no magnetic field? Or was it simply that the high pressure of the solar wind had compressed the magnetosphere more than had been expected?

Finally, at 7 a.m. on August 31, the first indication of the bow shock, at a distance of 24 R_S from the planet, was received at Ames. An hour and a half later, the shock, pushed inward by an increase in the solar pressure, passed the spacecraft, and Pioneer was again in interplanetary space. Not until a little after noon did it catch up with the bow shock. Finally, at about 5 p.m., Pioneer crossed the magnetopause—only 17 R_S from Saturn.

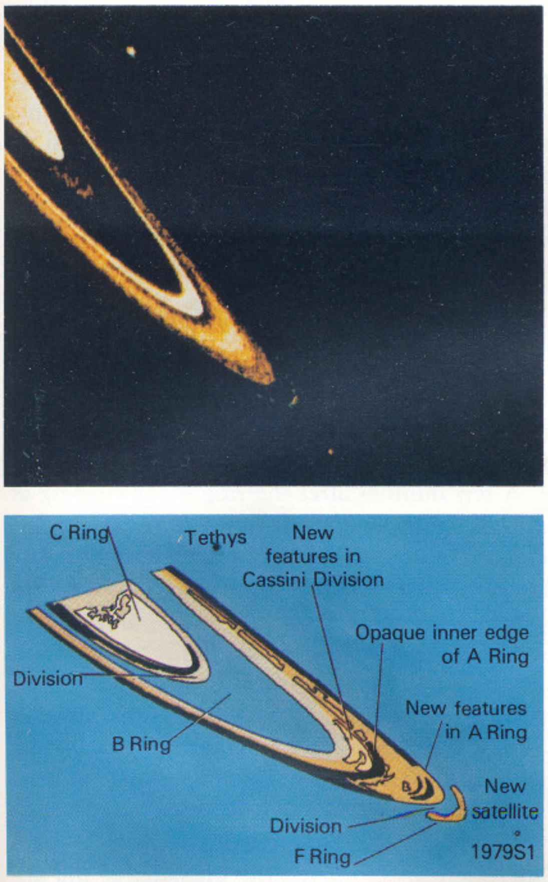
To the surprise of most scientists, Titan was outside the magnetosphere—or rather it would have been, had it been in the sunward facing part of its orbit. Subsequent calculations indicated, however, that this was an unusual case, caused by the very high level of activity on the Sun. Normally Titan would be inside the magnetosphere, and exceptions probably take place only occasionally, even during the peak years of the solar activity cycle.

During the last two or three days of August, while most of the investigators were preoccupied by the wait for the magnetosphere, the imaging polarimeter had begun to produce pictures of Saturn that exceeded in resolution any ever obtained from Earth. To the disappointment of experts on planetary atmospheres, however, the disk of Saturn revealed almost no detail. Clearly Saturn was very different from Jupiter; it lacked the striking alternation of dark belts and bright zones and the swirling, colorful storm systems that were so prominent on Jupiter.

The images of the rings proved more interesting. As seen by Pioneer, they were almost unrecognizable to astronomers accustomed to the usual view of the sunlit face. The Pioneer pictures, taken in light that diffused through to the unilluminated side, were almost a negative, with the normally brightest areas, such as the B Ring, appearing dark because of their opacity to transmitted light. The brightest parts of the rings as seen by Pioneer were the C Ring and the Cassini Division, both apparently containing just enough particles to transmit and scatter the sunlight back toward the spacecraft. Thus what was bright for

Pioneer were lightly populated parts of the rings. However, the areas that appeared dark were ambiguous—they could be regions that were opaque because of high particle density or regions that contained no particles at all to scatter the light. For example, the Pioneer investigators saw a dimmer region in the midst of the bright Cassini Division and thought it was an empty area; later it turned out that this dimming was the effect of more particles in the middle of the Division, not fewer.

Pioneer Saturn discovered a new ring—the F Ring—just a few thousand kilometers beyond the outer edge of the A Ring. This image obtained by the Pioneer photopolarimeter also shows a new satellite, provisionally called 1979S1. A few hours later the spacecraft nearly collided with the same satellite as it skimmed below the rings. It was later determined that 1979S1 was one of the two co-orbital satellites of Saturn first seen in 1966.



Perhaps the most exciting Pioneer image was obtained just after midnight on September 1, at a range from the planet of about 1 million kilometers, providing a resolution of about 1000 kilometers. This picture revealed a narrow new ring, called the F Ring, about 3000 kilometers beyond the outer edge of the A Ring. The F Ring was not resolved in the Pioneer pictures; it could have been any width up to about 1000 kilometers. The narrowness of this ring set it off from the other Saturn rings and was reminiscent of the Jupiter ring discovered by Voyager, or perhaps the still narrower rings of Uranus.

The same picture that revealed the F Ring also showed a new satellite inside the orbit of Mimas. Both S-10 (sometimes called Janus) and S-11 had been seen in this region in 1966, but it was not clear at first whether the Pioneer object was one of these, or if so, which one. Thus it was given the provisional designation 1979S1, for the first new Saturn satellite discovered in 1979.

As Pioneer plunged closer and closer to Saturn, the ultraviolet and infrared instruments observed the planet and the space around it. Saturn showed up strongly in the long-wave ultraviolet channel, sensitive to a broad range of wavelengths that included the brightest line (Lyman α) of atomic hydrogen. A more diffuse glow was seen from a large region that included the orbit of Titan, and there was further evidence of emission from the region of the B Ring, possibly an indication of a tenuous atmosphere of water vapor and hydrogen. Thermal infrared emission from Saturn provided a first measurement of helium in the atmosphere and a value for the global temperature: −180° C. This temperature, although low by most standards, was substantially higher than would be expected from the effect of sunlight alone; it yielded a value for the internal heat source of Saturn that was relatively higher than that for Jupiter. Saturn, radiating more than twice as much heat as it received from the Sun, apparently had an additional internal energy source not acting on Jupiter.

The critical crossing of the ring plane was expected at a spacecraft time of about 9:02 a.m. on September 1, 1979. At that moment, collisions with ring particles, even 38 000 kilometers beyond the visible edge of the A Ring, might destroy the spacecraft, but it would not be until 86 minutes later (10:28 a.m.) that the radio waves would reach Earth and the scientists and engineers waiting at Mission Control would know the truth. As the "moment of truth" approached, a hushed silence fell over the watchers. The countdown to expected ring plane crossing was broadcast across the nation on public radio and television, as well as throughout the sprawling Ames Research Center. At 10:28 the radio signal continued to be received. Another slow minute was ticked off in case the original time estimate had been in error. Still the data flowed back from Pioneer and were received at the Deep Space Network station in the Mohave Desert and relayed to Ames. Finally, Project Manager Charlie Hall said he thought we had made it. There were scattered cheers and many sighs of relief. A few rueful comments were also made about not having tried for the target point inside the rings. But there was little time for either celebration or regrets, since Pioneer was now on the most crucial leg of its journey, exploring space near Saturn that would probably not be visited by spacecraft again in this century. The closest approach to Saturn, just 21 000 kilometers above the clouds, would take place in 29 minutes. The speed of Pioneer at this time would reach 114 000 kilometers per hour.

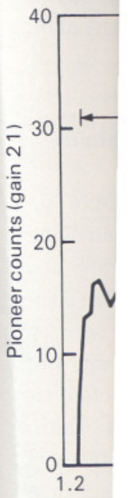
Near Collision With a Satellite

The Pioneer spacecraft, swinging under the rings to its closest approach to Saturn at a distance of 1.35 R_S, would traverse the part of the magnetosphere that was "shadowed" by the rings. Electrons and protons spiraling in Saturn's magnetic field should be depleted where the ring particles were densely packed or at the position corresponding to the orbit of a satellite. Thus a profile of the radiation belts should reveal the profile of solid material—rings or satellites—with a high level of sensitivity. James van Allen of the University of Iowa, the discoverer of the Earth's radiation belts, dubbed this technique "particle beam astronomy." It was anticipated that a definitive search could be made for small satellites or faint rings near the outer edge of the visible ring system.

Between the orbits of Rhea (8.8 R_S) and Dione (6.3 R_S), the maximum intensity of low-energy magnetospheric electrons was detected. As Pioneer crossed the orbit of Dione, a sharp dip in intensity was recorded. But the electron counts recovered only slightly, then continued to drop rapidly as the spacecraft neared the orbit of Tethys at 4.9 R_S. Values remained low on both sides of Enceladus, perhaps indicating absorption by the diffuse E Ring. There was a small maximum outside the orbit of Mimas (3.1 R_S), and then a rise to a maximum at 2.7 R_S, very close to the supposed orbit of S-10 (Janus). A maximum was inconsistent with the presence of a satellite, indicating that the nominal orbit for this inner satellite was in error.

Additional structure was detected in the charged particles, including the indication of the F Ring. At 2.292 R_S, the edge of the A Ring, the counts of charged particles of all energies dropped to zero. In the magnetic shadow of the rings, Pioneer found itself in the most radiation-free environment it had experienced since it sat in its shroud on top of an Atlas-Centaur rocket at Cape Canaveral six years before. On the outbound journey, the same signatures of the rings and satellites were seen in the charged particle measurements. But in the midst of this orderly mapping out of the Saturn radiation belts, Pioneer was to have an adventure.

A few minutes after the ring plane crossing at 2.82 R_S, as the spacecraft traversed the region between the orbit of Mimas and the F Ring, it nearly collided with a large object! The evidence appeared, not in the imaging data, but in the records from the particles and fields detectors. At 2.53 R_S, the counting rates on several energetic particle detectors suddenly and dramatically dropped for about 8 seconds, accompanied by alterations in the magnetic field. Apparently the spacecraft had passed right through the magnetic wake of a satellite. From the duration of the dropout, scientists estimated the diameter of the unknown object at about 200 kilometers and the



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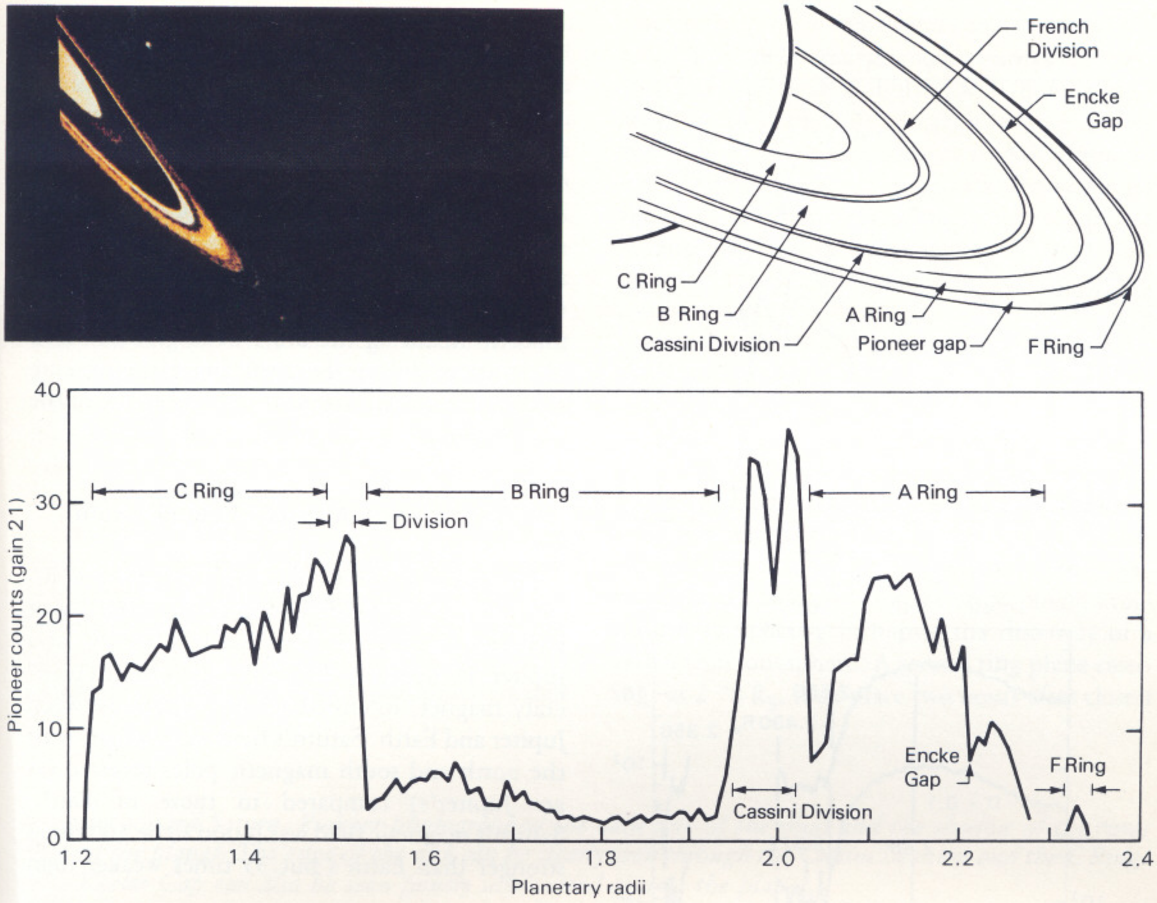


The Pioneer spacecraft was able to view the unilluminated side of the rings, providing a unique vantage point for their study. Seen from this angle, the brightest parts of the rings are those with a small number of particles, enough to scatter the sunlight but not so many as to make the rings appear opaque. The brightest region is the Cassini Division, with the C Ring only slightly dimmer. The least brightness corresponds to the opaque B Ring as well as to true gaps between the rings. The trace shows the brightness of the unilluminated side of the rings plotted against distance from Saturn, with an effective resolution of about 1000 kilometers.

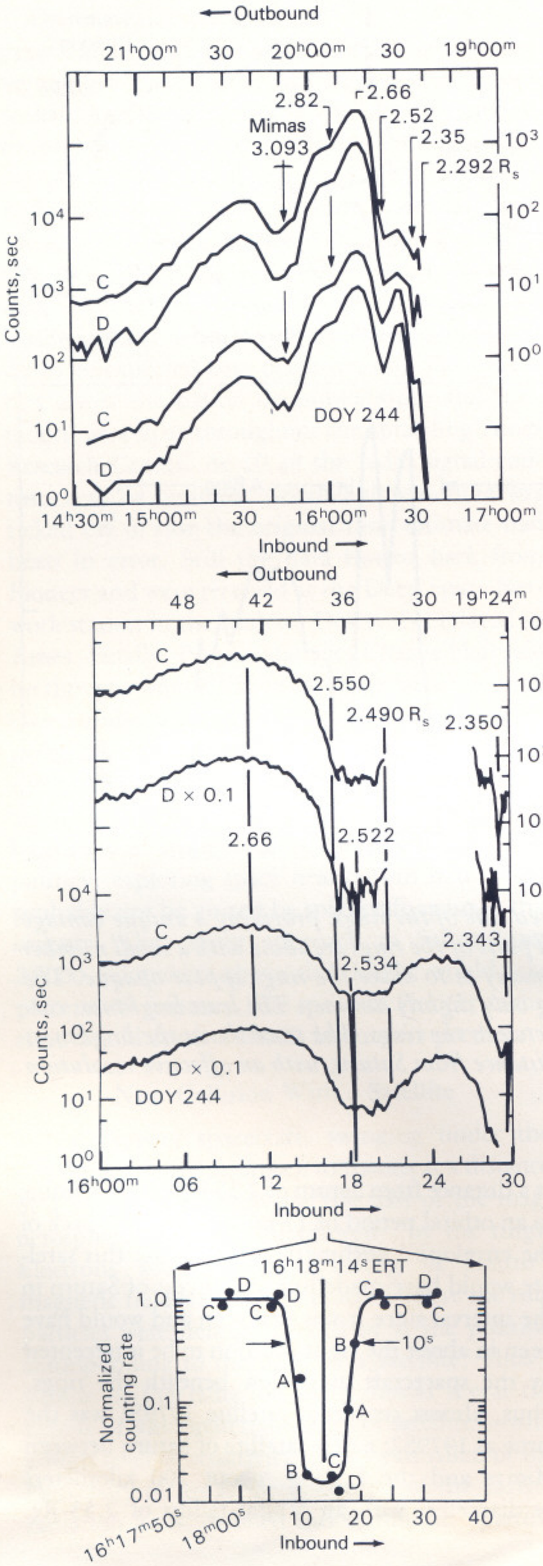
miss distance at less than several thousand kilometers. At this time the spacecraft was only about 2000 kilometers below the ring plane, where the unknown object was almost certainly orbiting. The new satellite, at 2.53 R_S, was called 1979S2. The chances of such a near collision were extraordinarily small, but once again the Pioneer luck had resulted in a major and quite unexpected discovery.

New satellite 1979S1, photographed by the Pioneer imaging system the previous day, was also at a distance from Saturn of 2.53 R_S, corresponding to an orbital period of 17 hours. A little "back of the envelope" arithmetic showed that this satellite would have made just one circuit of Saturn in the interval since it was first seen and would have been in about the right position to be intercepted by the spacecraft as it flew beneath the rings. Thus, almost certainly, satellite 1979S1 was the same as 1979S2: a new satellite of Saturn between Mimas and the F Ring, about 200 kilometers in diameter, with an orbital radius of 2.53 R_S.

This new satellite was certainly real—so real it had almost brought Pioneer to a premature end—but apparently Janus was not. At least, the orbit indicated for Janus from the 1966 observations (with a radius of 2.65 R_S) was wrong. Many scientists guessed that the new satellite, which was bright enough that it should have been visible when the rings were edge-on in 1966, probably accounted for some and perhaps most of the earlier observations, but that errors had been made in deducing the orbit. New ground-based observations during the 1980 ring plane crossing would be required to resolve the ambiguity of the existing data.

The Surprising Magnetic Field of Saturn

Before the Pioneer encounter with Saturn, intrinsic magnetic fields had been discovered and analyzed on three planets: Earth, Mercury, and Jupiter. Pioneer found Saturn to be a fourth planetary magnet, intermediate in strength between Jupiter and Earth. Saturn's field was dipolar, with the north and south magnetic poles reversed (as are Jupiter's) compared to those of Earth. Saturn's magnetic field was found to be 500 times stronger than Earth's but 35 times weaker than



The particles and fields instruments on Pioneer Saturn were used to search for unknown satellites and rings by measuring the absorption of energetic charged particles. The top figure shows the profiles of charged particle intensities as the spacecraft moved toward and away from Saturn. Drops in the counting rates show the absorption by Mimas and several other possible rings or satellites closer to the planet. Also shown is a very sharp drop in particle count at 2.52 R_S. The middle figure shows the absorption in greater detail. The lower figure shows the eight-second absorption of 1979S2. Scientists concluded that this peculiar effect must have been the result of Pioneer Saturn's passage through the magnetic wake of an unknown satellite, apparently missing collision by no more than a few thousand kilometers. This feature was later determined to be 1979S1, the satellite discovered by photography on the previous day.

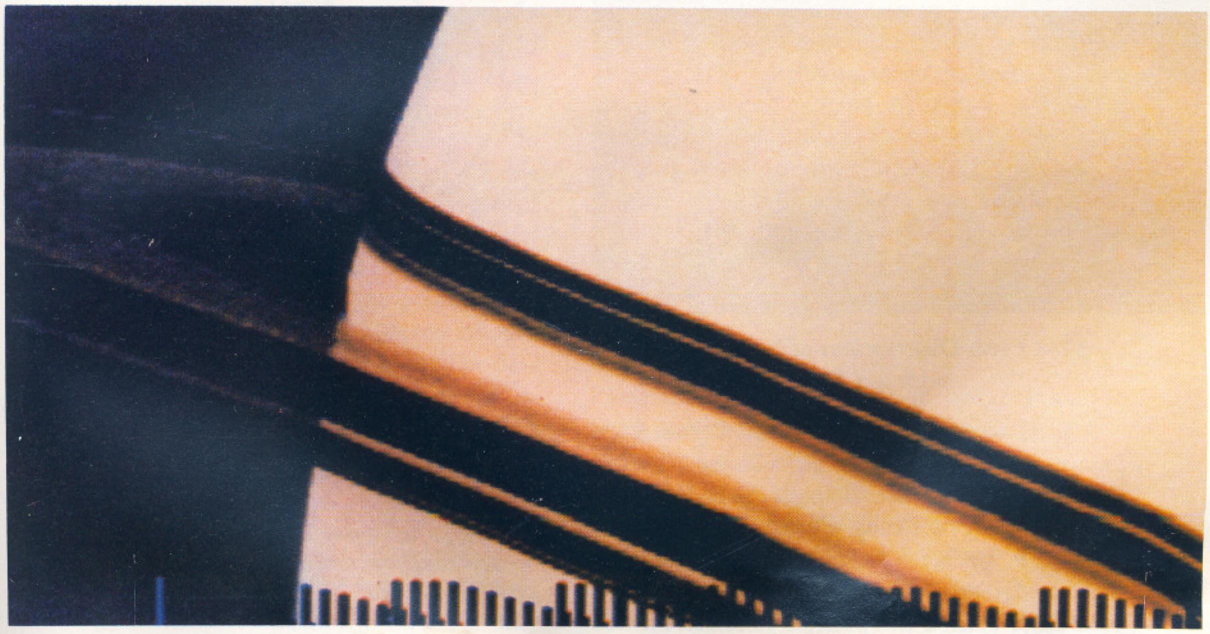
Jupiter's. These values refer to the total magnetic moment; at the surface of Saturn, which is much farther from the source than is the surface of Earth, the two fields have similar magnitude.

The most unexpected aspect of the magnetic field of Saturn was its close alignment with the rotational axis of the planet. The magnetic fields of Earth, Jupiter, and the Sun are tilted by about 10 degrees, and theorists had postulated that this difference between the magnetic and rotational axes was an important element of the internal dynamo process that generated the magnetic field. The discovery that Saturn's magnetic axis lines up almost exactly with the rotational axis necessitates a basic reexamination of the theory of planetary magnetism.

The magnetosphere of Saturn was unusually compressed during the Pioneer encounter, but even under normal conditions it would be substantially smaller than Jupiter's. In addition, the population of energetic particles—primarily electrons and protons—was found to be much smaller than in the Jovian radiation belts, primarily as a result of particle absorption by the satellites and rings. The belts are comparable in intensity to those of the Earth, but occupy a volume several thousand times larger than our own magnetosphere. Because of the alignment between the magnetic and rotation axes, the charged particles at Saturn do not experience the rotational wobble that characterizes the radiation belts of Jupiter and Earth.

Following its closest approach to Saturn on September 1, Pioneer Saturn retraced the route outward, continuing to skim just a few thousand kilometers beneath the rings. The view from the spacecraft would have been truly spectacular, but it was impossible to capture with the Pioneer imaging system. As seen from Earth, the spacecraft passed behind Saturn, and the radio occultation provided the first probe of the atmospheric structure of the planet, including the discovery of a rather thin ionosphere. A second ring plane crossing, at 2.78 R_S, took place two hours after closest

Looking toward Saturn, Pioneer photographed the dark side of the rings and the shadow of the rings against the planet. The edge of the disk can be clearly seen through the Cassini Division and the C Ring. The Keeler Gap can also be seen faintly silhouetted against the planet.



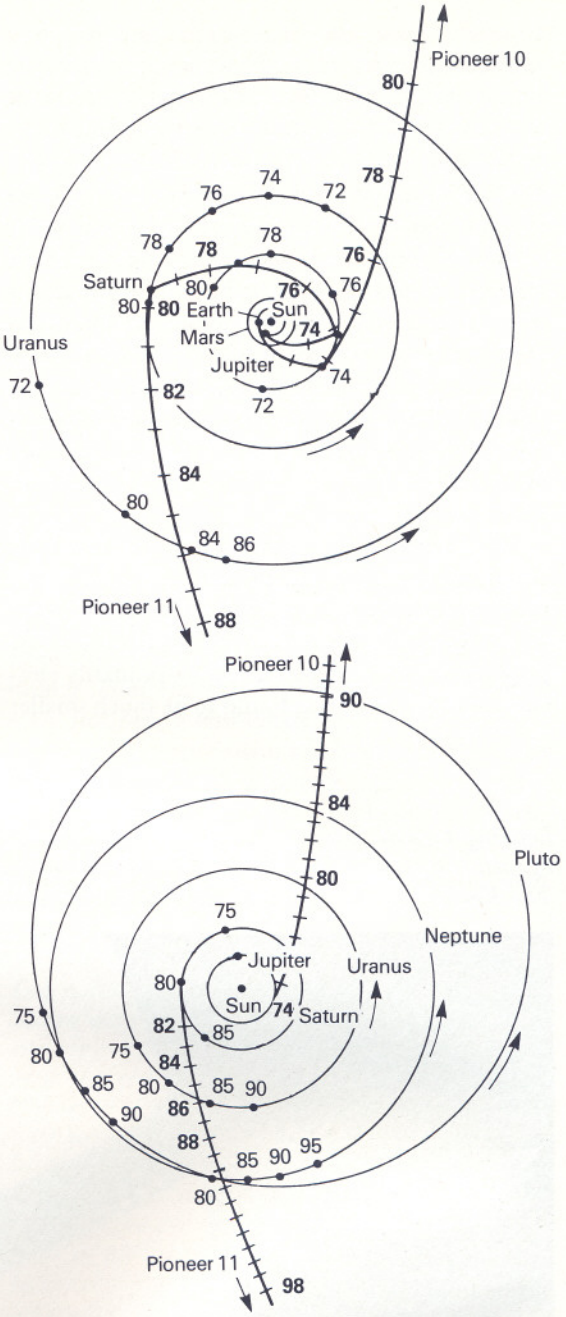
approach, without any indication of damage to the spacecraft.

On the outbound leg of its journey, Pioneer looked back at a crescent Saturn. Again it was on the opposite side of the rings from the solar illumination, so the C Ring and the Cassini Division appeared brightest. Just one day after the Saturn encounter, Pioneer crossed the orbit of Titan and made a few distant observations of that planet-sized satellite at a range of 363 000 kilometers. Not until the early morning hours of September 3 did it again reach the edge of the magnetosphere. Between September 3 and September 8 there were five magnetopause crossings and nine bow shock crossings before the spacecraft emerged permanently into the interplanetary medium. Meanwhile, the increasing proximity in the sky of Saturn and the Sun produced radio interference, and for several days in mid-September contact with Pioneer was lost completely. By October, however, all was back to normal, with the spacecraft now beyond the orbit of Saturn, measuring the solar wind.

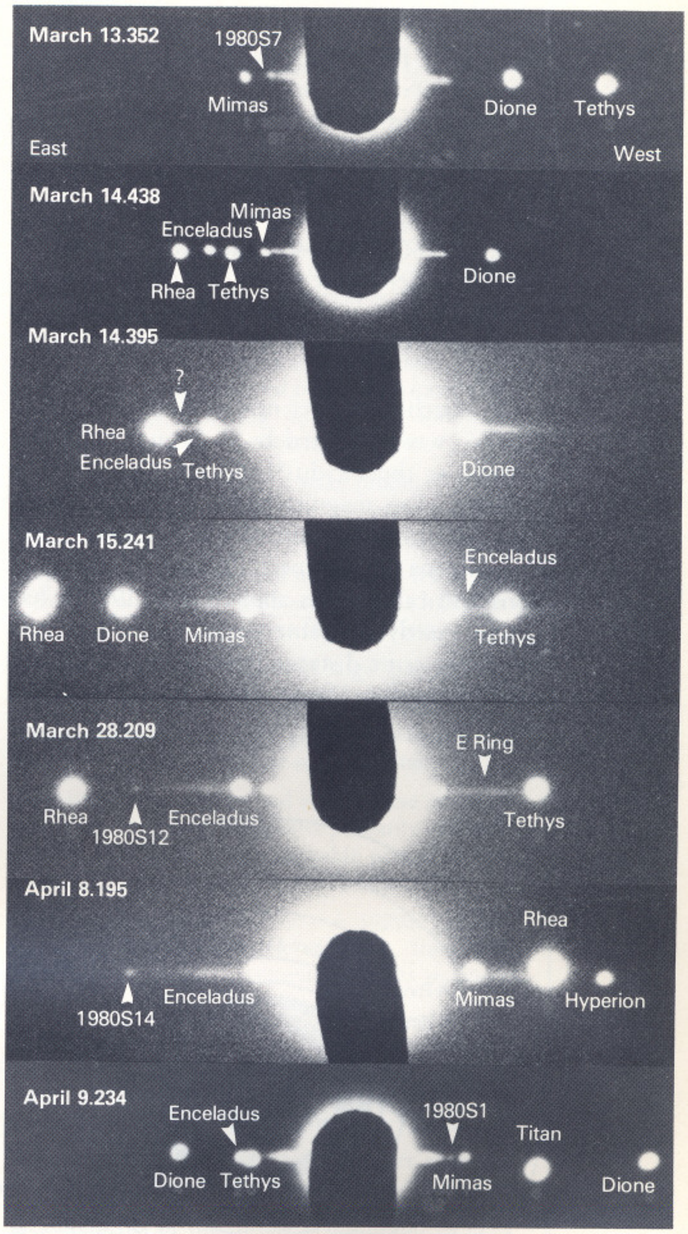
Pioneer Saturn became the second spacecraft to escape solar gravity completely and to leave the solar system and penetrate interstellar space. It is continuing to explore new regions, exiting from the solar system in a direction approximately opposite to that of its twin, Pioneer 10. As the first spacecraft to reach Saturn, Pioneer earned worldwide acclaim, and it formed the centerpiece for a *Newsweek* cover story on planetary exploration. As NASA's Tom Young, then Deputy Director of Ames, said "We welcome Saturn into our books of knowledge with a lot of pride that we did it. We can report to Voyager: 'Come on through, the rings are clear.'"

1980 Earth Observations of Saturn's Rings and Inner Satellites

A little more than a year passed between the Pioneer encounter with Saturn and the arrival of the more sophisticated Voyager spacecraft. This interval was of particular interest to astronomers, because it included the time at which the rings appear edge-on as seen from Earth. For the first time since 1966 it was possible to search for new



The two Pioneer spacecraft were the first human artifacts to escape entirely from the solar system. Pioneer 10 began the outbound leg of its journey in 1973 following its flyby of Jupiter. The second Pioneer, after flying past Saturn in late 1979, continued outward in a direction almost opposite to that of its twin. By 1990 both spacecraft will be near the orbit of Pluto.



In 1980 the rings of Saturn were turned edge-on to the Earth, providing an opportunity to search for otherwise invisible small satellites near the rings. Here are shown a series of photographs taken at the University of Arizona with a CCD camera at the 1.5-meter telescope of the Catalina Observatory. Several new objects are pointed out, labeled with their provisional designations. These designations (such as 1979S3) would be used until definite orbits for each new object could be determined. During the ring plane crossing, extensive observations were made of the two co-orbital satellites (S-10 and S-11), and the small satellite Dione B (or S-12) was seen for the first time. Photo courtesy of Bradford Smith, University of Arizona.

inner satellites and faint rings, taking advantage of the virtual absence of the bright rings as they dwindled to an almost invisible line in even the largest telescopes. Also, it was anticipated that the ambiguities concerning S-10, S-11, and the satellite discovered by Pioneer could be resolved.

The main focus of activity at many observatories around the world was the photographic search for faint inner satellites near the edge of the rings. In the United States, at Lowell Observatory and at the University of Arizona, this project was greatly enhanced by the introduction of a special new imaging detector, the charge coupled device (CCD), developed by NASA for the cameras on the Space Telescope. Other programs were carried out at the Pic-du-Midi Observatory in France, the Jet Propulsion Laboratory's Table Mountain Observatory, McDonald Observatory of the University of Texas, and Mauna Kea Observatory of the University of Hawaii.

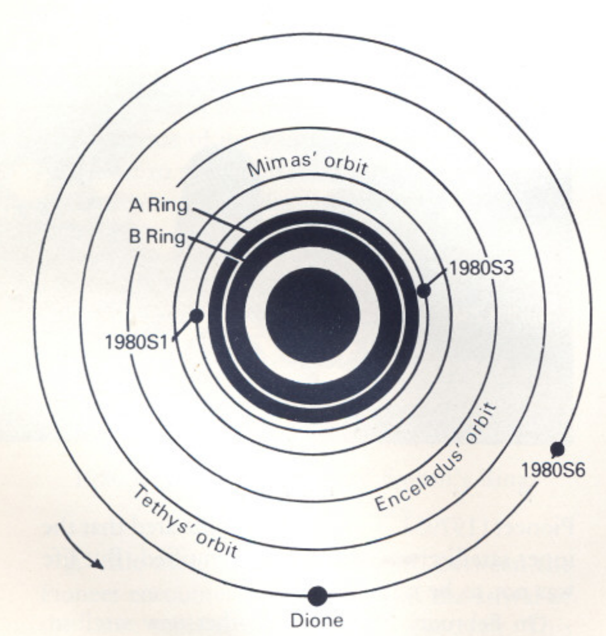
The first reported sighting of a new satellite was made in Texas on December 9, 1979, but it could not be followed up to calculate an orbit. The next discovery was object 1980S1, first detected by Bradford Smith and his colleagues at the University of Arizona on February 6, 1980. It soon became apparent that 1980S1 was one of the objects that had been seen in 1966. It was seen several more times in France and Arizona and an orbital period of 16.67 hours was determined, matching the orbit of the satellite discovered by Pioneer (1979S1 = 1979S2). It appeared that the inner satellite was now firmly identified. But life was not to be so simple.

On February 26, 1980, another new satellite, designated 1980S3, was observed by University of Hawaii astronomer Dale Cruikshank at Mauna Kea Observatory; on March 1 it was also picked up by the University of Arizona group, and on

March 15 at Table Mountain Observatory. The orbital period for 1980S3 was virtually identical to that of 1980S1, but the object was different. Here was a unique discovery—two satellites in the same orbit but on approximately opposite sides of the planet! This discovery also introduced a much greater ambiguity into earlier observations, both those in 1966 and those from Pioneer. It was impossible to determine which of the two co-orbital satellites had been seen when. Scientists began to call them S-10 and S-11, but the designation was arbitrary.

On March 1 another new satellite, designated 1980S6, was discovered by P. Laques and J. Lecacheux at the Pic-du-Midi. The same satellite—fainter than magnitude 16, but relatively far from Saturn—was recorded a few hours later by the Arizona astronomers. Subsequent observations and calculations showed that 1980S6 had almost exactly the same period (2.74 days) and was at the same distance from Saturn (6.3 R_S) as the large satellite Dione. The new satellite, called S-12 or Dione B, was another co-orbital object. Apparently, it was in a stable configuration with Dione, preceding it by about 70 degrees in orbital longitude and occupying one of the permitted Lagrangian points of Dione's orbit. In the space of a few days, two examples of a new phenomenon, co-orbital satellites, had been discovered.

The rings of Saturn were the subject of careful measurements as they appeared edge-on. From their faintness, it was again shown that the rings are extremely thin—almost certainly less than 2 kilometers. A CCD search for the E Ring carried out at Lowell Observatory by William Baum and his colleagues clearly established for the first time the existence of the E Ring and its approximate dimensions. From their measurements, the astronomers at Lowell Observatory found that the E Ring was limited to an area near the orbit of Enceladus. They speculated that Enceladus might be the origin of the E Ring material, although no specific mechanism seemed likely. Was there something special about this satellite?



After the 1979 ring plane crossing and before the first Voyager encounter of Saturn, a total of twelve Saturn satellites were known. Two of these, 1980S1 and 1980S3, also called S-10 and S-11, were in essentially the same orbit. One was slowly catching up with the other, apparently headed for a collision in late 1981 or early 1982. Before these two satellites would collide, however, it is expected that they will interact gravitationally, shift orbits, and move slowly apart without damaging each other.

PIONEER JUPITER SCIENCE HIGHLIGHTS

Confirmation that Jupiter emits more heat than it receives from the Sun, and measurement of its internal energy source at 10^{17} watts.

First measurement of the amount of helium in the atmosphere, indicating that the ratio of helium to hydrogen is similar to the value for the Sun.

Location of the minimum temperature in the atmosphere (− 165° C) at a pressure of 0.03 bar.

Determination from gravity and temperature measurements that Jupiter is fluid throughout (with the possible exception of a small metallic core), and has no solid surface.

Measurement of the global magnetic field of Jupiter, showing that it is dipolar, with a magnetic axis tilted by 11 degrees and offset 10 000 kilometers from the rotational axis, and a dipolar moment 18 000 times greater than that of Earth.

Improvements in mass determinations for the Galilean satellites, leading to better models for their interior structure.

Discovery from radio occultation data of an ionosphere on Io, with substantial differences between the two locations measured.

Strong ultraviolet emission, possibly due to atomic hydrogen, from a region near the orbit of Io.

Determination that the outer boundary of the Jovian magnetosphere is near 100 R_J in the direction from which the solar wind is flowing, and farther in the downwind direction.

Discovery of a strong current sheet of electrons circling Jupiter in its magnetic equator and extending to about 60 R_J.

Characterization of the strong concentrations of electrons and ions in the inner magnetosphere, trapped in the planet's magnetic field and rotating with it. The peak strength of the radiation belts was located inside the orbit of Io, near 3 R_J.

Measurement of structure in the inner magnetosphere due to particle interactions with the satellites, including the suggestion of an unknown satellite or ring near 1.8 R_J.

PIONEER SATURN SCIENCE HIGHLIGHTS

Discovery of the magnetic field of Saturn, found to be dipolar, with a dipole moment 500 times greater than Earth's, and (surprisingly) to be aligned with the rotational axis of the planet.

Discovery of the magnetosphere of Saturn, extending to about the orbit of Titan in the direction of the solar wind and to greater distances away from the Sun.

Confirmation that energetic charged particles in the magnetosphere are absorbed by Saturn's inner satellites and rings, resulting in radiation intensities hundreds of times weaker than at Jupiter.

Measurements of a magnetic wake produced by the interaction of Titan with the co-rotating Saturn magnetosphere.

Confirmation of an internal heat source on Saturn, with the planet radiating about two and a half times as much energy as it receives from the Sun.

Confirmation of the absence of large spots or other striking cloud features in close-up photographs.

Measurement of ultraviolet glows from Saturn and from a wide region near the orbit of Titan.

Calculation from gravity and temperature measurements that Saturn is composed primarily of liquid metallic hydrogen, with a probable core of heavier material about ten Earth masses in size.

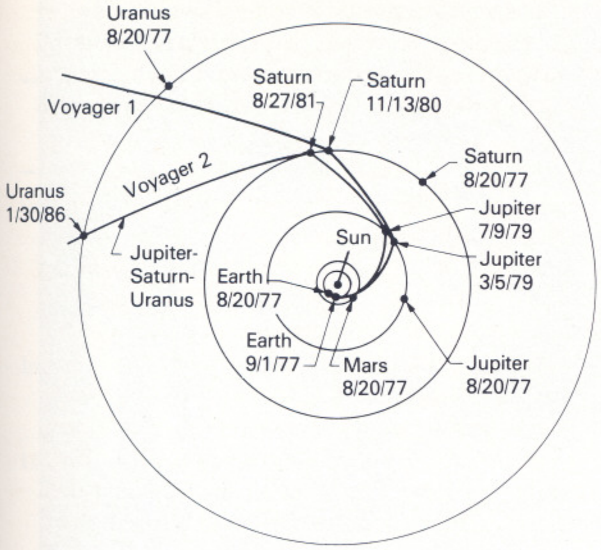
Discovery of a satellite (1979S1 = 1979S2) at 2.53 R_S, about 200 kilometers in diameter, from both imaging and direct measurements of its magnetic wake.

Demonstration from charged particle measurements that there is no satellite in the reported orbit of Janus, but that several other undiscovered inner satellites or rings may be present.

Discovery of the F Ring, much thinner than the other known rings of Saturn, outside the A Ring.

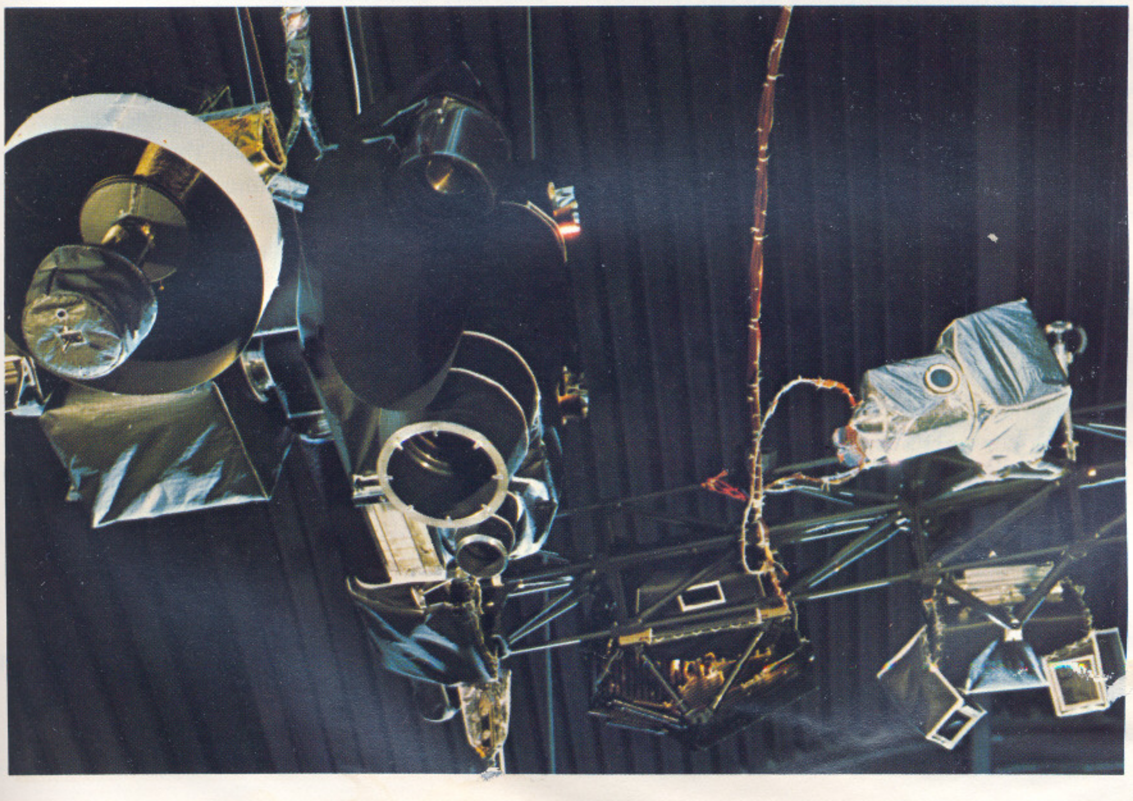
Measurements of the diffuse transmission of light through the rings, including indication of substantial material within the Cassini Division.

Demonstration that a spacecraft can penetrate the E Ring without damage.



Each Voyager spacecraft followed a billion-kilometer path to Jupiter, where the gravitational pull of the giant planet was used to redirect the trajectory toward Saturn. Voyager 1 received a larger kick from the gravitational slingshot than Voyager 2, increasing its lead so that it arrived at Saturn in November 1980, about nine months before Voyager 2. Following the Saturn flyby, Voyager 1 continued out of the solar system while Voyager 2 used the Saturn flyby to redirect its path toward a Uranus encounter in 1986.

The Voyager scan platform contains instruments that gather data for Voyager's remote sensing investigations. Five of these instruments—two TV cameras, the infrared spectrometer, the ultraviolet spectrometer and the photopolarimeter—are mounted together on the scan platform, which can be pointed to any direction in space to allow exact targeting of the observations. (373-7146BC)



Voyager Project Scientist Ed Stone (left) discusses a sequencing problem with his deputy, Ellis D. Miner. (P-23311AC)

They were in almost exactly the same orbit but on nearly opposite sides of the planet. However, the orbital periods differed just enough for the two satellites to approach each other at about 9 meters per second relative speed. Many scientists wondered what would happen in about a year and a half when the two satellites passed very close to each other. Presumably they would interact and shift orbits, but the details were purely speculative.

October 24, 1980 (25 million km)

With imaging resolution better than 500 kilometers and the ring filling the narrow-angle camera field of view, Voyager passed from the observatory phase to the far encounter phase. Scan platform instruments other than the cameras were beginning to observe the Saturn system. The ultraviolet spectrometer (UVS) detected strong emission from hydrogen, not only from the planet but also from a diffuse region extending as far as the orbit of Titan. However, the preliminary observations did not show the doughnut-shaped torus at the orbit of Titan that had been predicted by many investigators.

The infrared spectrometer (IRIS) obtained spectra of Saturn several times each day, from

The scientific data radioed from the Voyager spacecraft were first received at JPL in the science control room. Here scientists could take a quick look at the numbers being produced by their instruments and verify that the spacecraft systems were operating correctly. (P-23162BC)

SATURN AND THE MIND OF MAN

On November 9, as the Voyager spacecraft was preparing for its historic encounter with Saturn, a special public program, dedicated to a discussion of the place of Saturn and of the Voyager exploration in a cultural and historical sense, was being held at the California Institute of Technology. Similar programs had been held at the time of the Mariner 9 orbit of Mars, again just before the first Viking landing on Mars, and in 1979 as Voyager 1 approached Jupiter. The panel discussions attracted a wide audience and were filmed for later television broadcast. Although aimed at the general public, the discussions were also fascinating for the Voyager scientists who were happy to spend a few hours away from the intense concentration on the minutia of the encounter to reflect on the broader historical importance of the exploration in which they were participating.

Five distinguished scientists and humanists were on the panel to discuss Saturn and the mind of man. The Chairman was Walter Sullivan of the *New York Times*, considered the dean of science writers in the United States. On the panel were Philip Morrison of the Massachusetts Institute of Technology, who was making his first appearance on one of these panels; Carl Sagan of Cornell University; novelist and poet Ray Bradbury; and Bruce Murray, Director of the Jet Propulsion Laboratory.

The panel was introduced by Marvin Goldberger, the President of Caltech, and concluding comments were made by the Governor of California, Jerry Brown, and his science advisor and former astronaut Rusty Schweigert.

Walter Sullivan began the discussion by reviewing the mythology associated with Saturn and its satellites. Philip Morrison continued with the thought that Saturn, in a sense, gave the world time, since its period of revolution around the Sun provided the longest natural time period to ancient peoples, a period not much less than a typical human lifetime. He also emphasized the extraordinary hold that this planet has on our imaginations because of the beauty of its rings. Morrison said, ''Of everything revealed by the telescope, the most meaningful to most people is the rings of Saturn.'' These beautiful features are very real and well known to us, yet invisible without the telescope. They are vast, but nearly transparent, ''all surface and no volume, all show and no substance.''

Carl Sagan also mentioned the significance of Saturn for ancient peoples. He noted that ''the following of the motions of the planets, an attempt to understand them, led to modern science and modern civilization.'' But to our ancestors, ''the planets were not places, not something to be visited.'' That is a new concept for humanity and it is, after all, only in the last two decades that we have had the capability to visit other worlds and to make them seem real to us. In many ways the Voyager flyby of Saturn was the culmination of this period of exploration. Sagan said, ''We are at the end of the first extraordinary stage of planetary exploration where all the wandering lights known to ancients are about to be visited and scrutinized by these wonderful, sophisticated robots we send out to explore the solar system. I believe we are at a moment that will be remembered for tens, hundreds, perhaps even thousands of years. It is with no small rapture that we now, today, view the system of Saturn's rings and fifteen moons. The Voyager results so far are truly stunning. We now see more than 100 separate rings. We see markings on tiny disks, little worlds that have never individually been the subject of a single scientific paper. We are at a moment of extraordinary discovery. There are six or eight new worlds up there that we are about to see for the first time.'' How much does this exploration cost? Sagan estimated that Voyager was costing about 1 cent per world explored per person on Earth. ''The exploration of the solar system is an extremely strong affirmation of being alive, of being curious about our place in space.''

Ray Bradbury emphasized the importance of exploring the solar system for our sense of humanity, especially in a period in which we have so much uncertainty about so many other things in our lives. He said, ''We have been living in an affluent period of despair.'' But we are exploring our solar system and we are learning a great deal. ''The day mystery dies is the last true day on Earth.''

Bruce Murray examined the achievement of the Voyager program. ''Voyager is the climax of a glorious decade of exploration. This has been an American cultural, as well as technical, triumph. We have come an enormous distance in space and in time and in intellectual development.'' Voyager is an extraordinary achievement. Murray emphasized that for the first time in history, a major exploration had to be done truly remotely. The spacecraft had to travel for years through space unattended, and during an encounter at the distance of Saturn the light travel time is so great that controllers could not even operate it by telemetry. We had to build an independent robot craft. ''If we try to do things that are nearly impossible, we will develop muscles, and those muscles are important.''

Carl Sagan articulated the thoughts of many when he said in a concluding statement that there is an unsaturated zest for scientific exploration that we all share. Mankind has always been characterized by this desire for knowledge. ''The exploratory instinct which has taken us to the vicinity of Saturn is part of the reason for our success as a species.''

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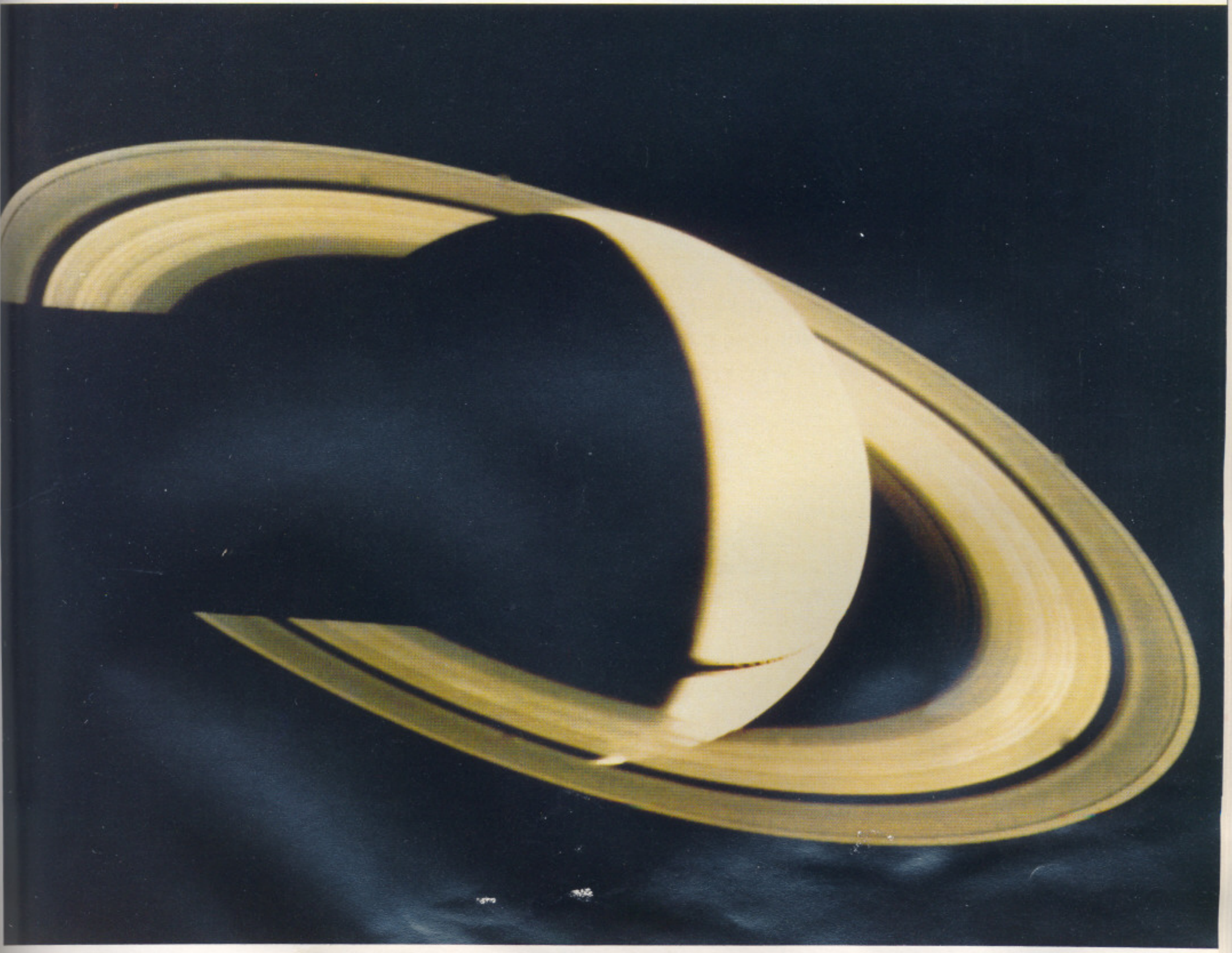
Discussing the implications of Saturn and the Mind of Man are (left to right) Philip Morrison of MIT, Carl Sagan of Cornell, Walter Sullivan of the New York Times, *Bruce Murray of JPL, and author and poet Ray Bradbury. (P-23340AC)*

In the weeks after the encounter, as the Voyager 1 spacecraft sped outward beyond Saturn, it transmitted this spectacular view of the ringed planet from a perspective never before witnessed by humanity. (P-23254)

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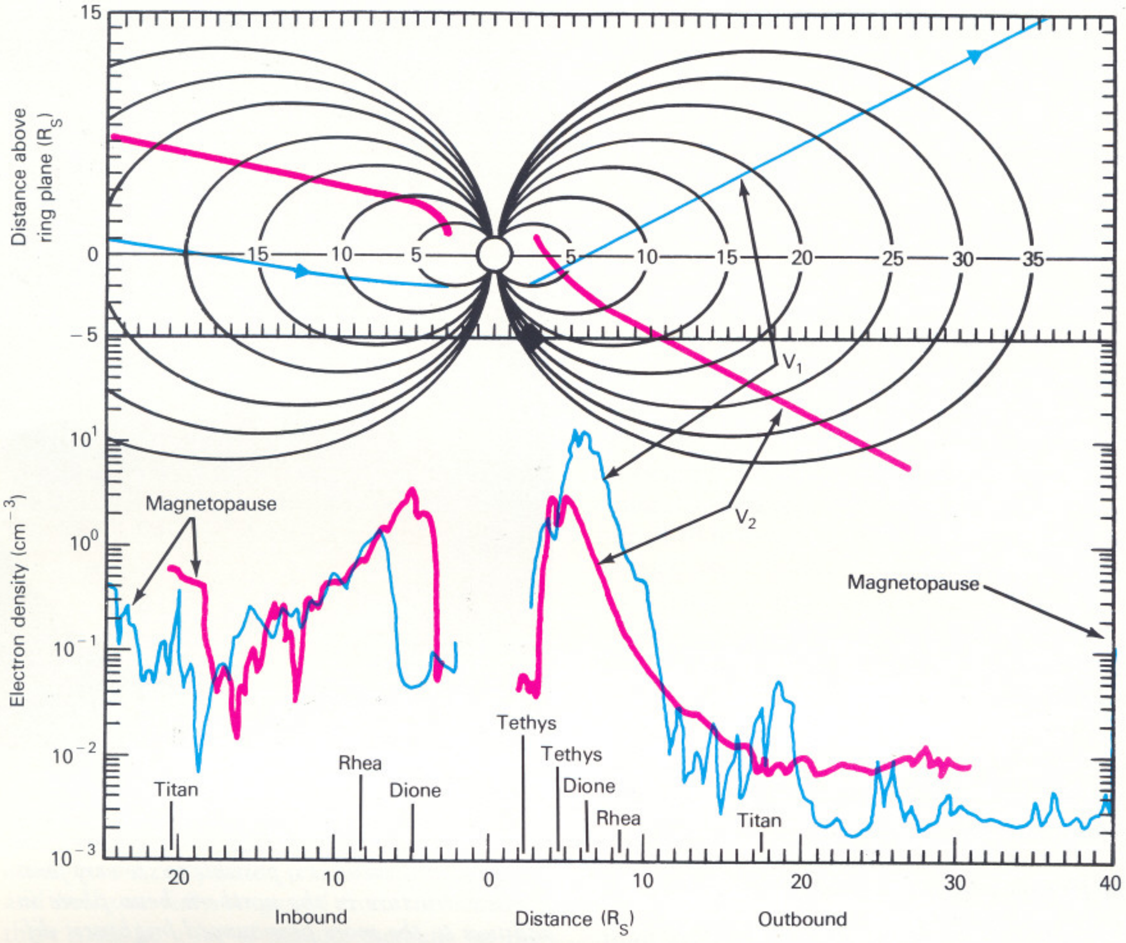
Press coverage of the Voyager 2 Saturn encounter exceeded that afforded any previous unmanned space mission. During the days around encounter, Von Karman Auditorium at JPL was packed with hundreds of members of the press, as well as Voyager scientists and engineers. (a) Behind the assembled press is a full-scale mock-up of the Voyager spacecraft. (b) Project Manager Ek Davis, Project Scientist Ed Stone, and Imaging Team Leader Brad Smith in a familiar pose answering questions from the rostrum. (c) A view of the busy press room. (d) JPL's Al Hibbs prepares to interview Gary Hunt for the daily television coverage that was beamed nationwide by the Public Broadcasting System. (P-24128DC, P-24051BC, P-24127AC, and P-24127BC)

to save it for Uranus. Many scientists, on the other hand, asked why some effort could not be made to move the scan platform to point at Saturn. Even if the usual intricate maneuvers were given up, just photographing Saturn and its rings instead of blank space seemed the logical thing to do. Project managers set a middle course, not trying at once to turn the platform back toward Saturn, but beginning to exercise it a step at a time to see if they felt confident enough to return to the planet.

August 27, 1981

At the regular morning press briefing, Ek Davis reported some progress in bringing the scan platform back to operational status. During the night the spacecraft had successfully responded to the



The density of plasma in the inner magnetosphere is affected by the satellites, which are both sources and sinks of energetic charged particles. In the upper part of the figure we see the regions of the magnetosphere sampled by the two Voyager spacecraft on their different trajectories through the system. At the bottom electron measurements with the plasma particle detector are shown for the Voyager 1 and Voyager 2 encounters.

planet provide the source. Saturn has both a metallic hydrogen core and rapid rotation, so it is not surprising that its field is second only to that of Jupiter among the planets we have visited with spacecraft. Although the intrinsic field is much larger than that of Earth, the actual surface fields (0.2 gauss at the equator) are a little smaller than our own, because of the larger distance of the surface from the interior source.

On the other two planets with well-observed magnetic fields, Earth and Jupiter, the alignment of the magnetic poles is considerably different from the rotational poles—they are tilted at an angle and offset from the center of the planet. It was therefore with great surprise that the Pioneer Saturn investigators found that the magnetic axis of Saturn was aligned almost exactly with the rotational axis. This alignment was confirmed by Voyager: the relative tilt of the two axes is only 0.7 degree, and there is no measureable offset at all. The resulting external magnetic field is almost perfectly symmetrical around Saturn, with none of the wobbly characteristics of Jupiter and Earth. This discovery has discomfitted theorists, who had

APPENDIX A

Voyager Science Teams

Cosmic Ray

Rochus E. Vogt, California Institute of Technology, Principal Investigator
J. Randy Jokipii, University of Arizona
Frank B. McDonald, Goddard Space Flight Center
Edward C. Stone, California Institute of Technology
James H. Trainor, Goddard Space Flight Center
William R. Webber, University of New Hampshire
Al W. Schardt, Goddard Space Flight Center

Infrared Interferometry and Spectrometry

Rudolph A. Hanel, Goddard Space Flight Center, Principal Investigator
Barney Conrath, Goddard Space Flight Center
Dale Cruikshank, University of Hawaii
F. Michael Flasar, Goddard Space Flight Center
Daniel Gautier, Observatoire de Paris, France
Peter Gierasch, Cornell University
Shailendra Kumar, University of Southern California
Virgil Kunde, Goddard Space Flight Center
William Maguire, Goddard Space Flight Center
John Pearl, Goddard Space Flight Center
Joseph Pirraglia, Goddard Space Flight Center
Cyril Ponnamperuma, University of Maryland
Robert Samuelson, Goddard Space Flight Center

Imaging Science

Bradford A. Smith, University of Arizona, Team Leader
Geoffrey Briggs, NASA Headquarters
Allan F. Cook II, Center for Astrophysics
G. Edward Danielson, California Institute of Technology
Merton E. Davies, Rand Corp.
Gary E. Hunt, University College, London
Torrence V. Johnson, Jet Propulsion Laboratory
Harold Masursky, U.S. Geological Survey
Tobias Owen, State University of New York, Stony Brook
Carl Sagan, Cornell University
Laurence Soderblom, U.S. Geological Survey, Deputy Team Leader
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The Voyager Science Team principal investigators and team leaders at JPL for the Jupiter flyby.

A final Voyager investigation did not require a special instrument at all. The radio telemetry link between the spacecraft and controllers on Earth was also used to probe the atmospheres of the planets and satellites, and special tracking of the spacecraft revealed the masses of planets and satellites as the spacecraft passed near them.

Remote Sensing Instruments

The eyes of Voyager are in its imaging system. Two television cameras, each with a set of color filters, look at the planets and their satellites and transmit thousands of detailed pictures to Earth. Unlike other Voyager instruments, the imaging system is not the result of a competition among proposals submitted by groups of scientists. The Voyager cameras were built by the Jet Propulsion Laboratory to be integrated with the design of the Voyager spacecraft and its subsystems. Members of the Imaging Science Team were selected individually on the basis of the scientific studies they proposed to carry out. The Team Leader is Bradford A. Smith, an astronomer from the University of Arizona; the Deputy Team Leader is Laurence A. Soderblom of the U.S. Geological Survey in Flagstaff, Arizona. Originally there were seven other members of the Imaging Science Team, but by the time of the Saturn encounter, the membership had been expanded to 26 scientists.

Both wide-angle and narrow-angle television cameras are required to obtain the highest possible resolution while retaining the capability to study global-scale features on the giant planets. The wide-angle camera has a focal length of 200 millimeters, providing a field of view of about 3 degrees, similar to that obtained with the 500-millimeter telephoto lens on a 35-millimeter camera. The narrow-angle camera has a focal length of 1500 millimeters and a field of view of 0.4 degrees. The detectors are selenium-sulfur vidicon television tubes, 11 millimeters square, designed for slow-scan readout, requiring 48 seconds to produce each picture. These are black and white television systems, but they can be used to produce color images by combining data from pictures taken successively through different colored filters.

Each image contains a tremendous amount of information, much more than is found in a commercial television picture. In computer termi-

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Plasma wave

Low energy
particles

Cosmic ray

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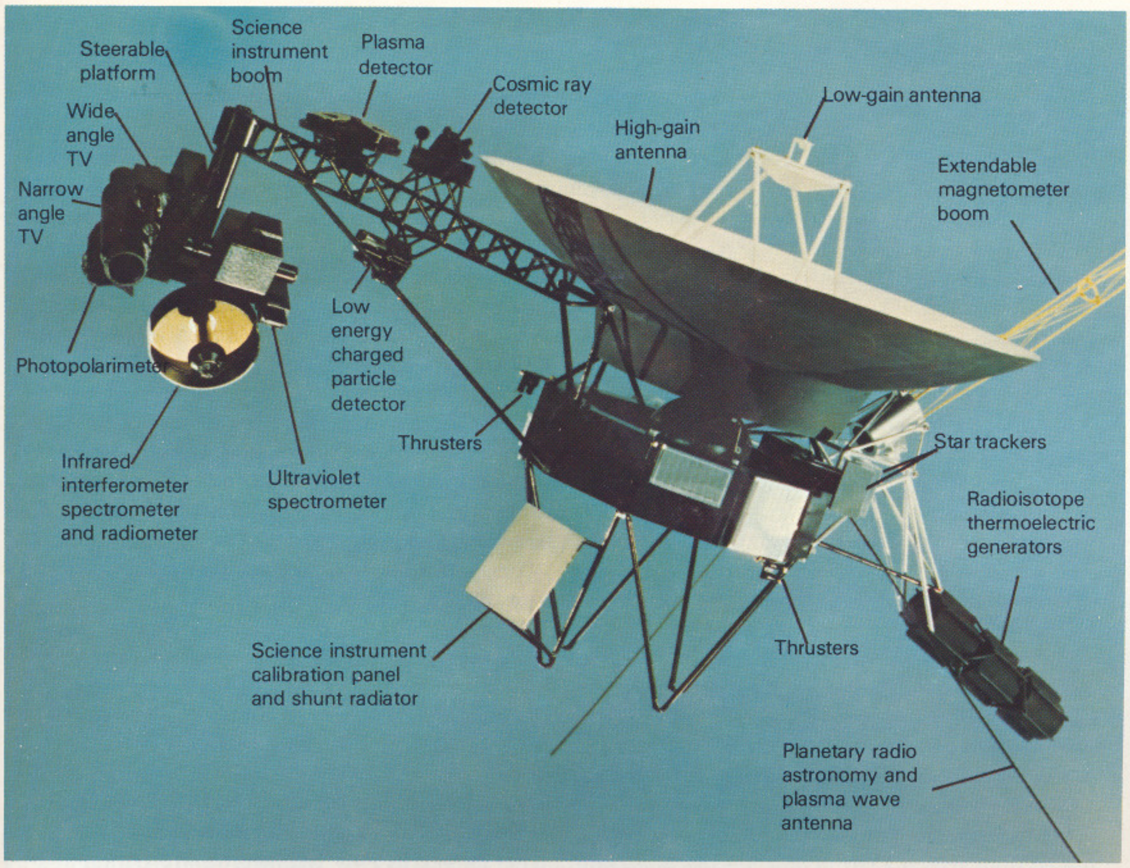

The fully deployed Voyager spacecraft is capable of a wide variety of direct and remote sensing measurements. Because of the exploratory nature of the Voyager mission, every effort was made to fly versatile instruments that could yield valuable results no matter what the nature of the Jovian and Saturnian systems. (P-18811AC)

thousand electron volts. A different instrument is required to measure the smaller numbers of particles that move at higher speeds. The low energy charged particle (LECP) instrument measures energies as high as several million electron volts, corresponding to a few percent of the speed of light. The Principal Investigator for the LECP is Stamatios M. Krimigis, a physicist from Johns Hopkins University, Baltimore, Maryland. The LECP instrument has two parts, designed respectively to measure particles trapped in the magnetosphere of a planet such as Jupiter or Saturn and to measure particles in the lower-density environment of interplanetary space.

A third particle instrument measures very high-energy particles, which are often called cosmic rays. The Principal Investigator for the cosmic ray instrument is Rochus E. Vogt, a physicist at the California Institute of Technology. Among his six co-investigators is Ed Stone, the Voyager Project Scientist.

The Voyager Spacecraft

The two identical Voyager spacecraft, each with a mass of 815 kilograms, are among the most autonomous, sophisticated robots ever sent to explore other worlds. Each is a self-contained system, carrying its own power, propulsion, communications systems, and science instruments.

Communication between the spacecraft and Earth is carried out via a high-gain radio antenna 3.7 meters in diameter that is always oriented