VOYAGER 2's ENCOUNTER WITH THE GAS GIANTS

When future generations look back, Voyager's epic journey to the four giant gas planets of our solar system may stand as one of humanity's most productive exploratory missions.

Ellis D. Miner

It was 3:40 am Pacific daylight time, 25 August 1989. I had watched with fascination a video display of Voyager 2's radio signal after the spacecraft had passed through Neptune's thick atmosphere, and for the last 90 minutes I had been attempting to nap in a sleeping bag on the floor of my office at JPL. My computer had just awakened me with a reminder that the first of 23 high-resolution pictures of Neptune's moon Triton was about to appear on the small monitor on my desk. The adjacent office was crowded with a dozen or so of my coworkers excitedly anticipating the same pictures. The first image appeared on my screen; boisterous cheering simultaneously erupted from next door. All thoughts of sleep fled, and for the next two hours I, along with dozens of other Voyager personnel and millions of interested onlookers around the world, exulted in the amazing scenes being transmitted by a small robot more than 4.4 billion km (4.1 light-hours) away. Humanity was seeing for the first time the surface features of the most distant moon in our solar system.

The extraordinary successes of the unmanned Voyager missions to the giant outer planets cannot be attributed entirely to fortunate happenstance. A spacecraft design based on the proven Mariner series of planetary probes contributed greatly to Voyager's hardiness. The Titan–Centaur rockets that hoisted Voyager 2 and Voyager 1 from their Cape Canaveral launch pad on 20 August 1977 and 5 September 1977, respectively, were also tested and reliable. The on-board computers and those at JPL had been programmed to detect and correct problems with the spacecraft. However, the success of the Voyager mission is most directly attributable to the dedication and expertise of those same individuals who so enthusiastically enjoyed the fruits of their labor in the wee hours of that August morning.

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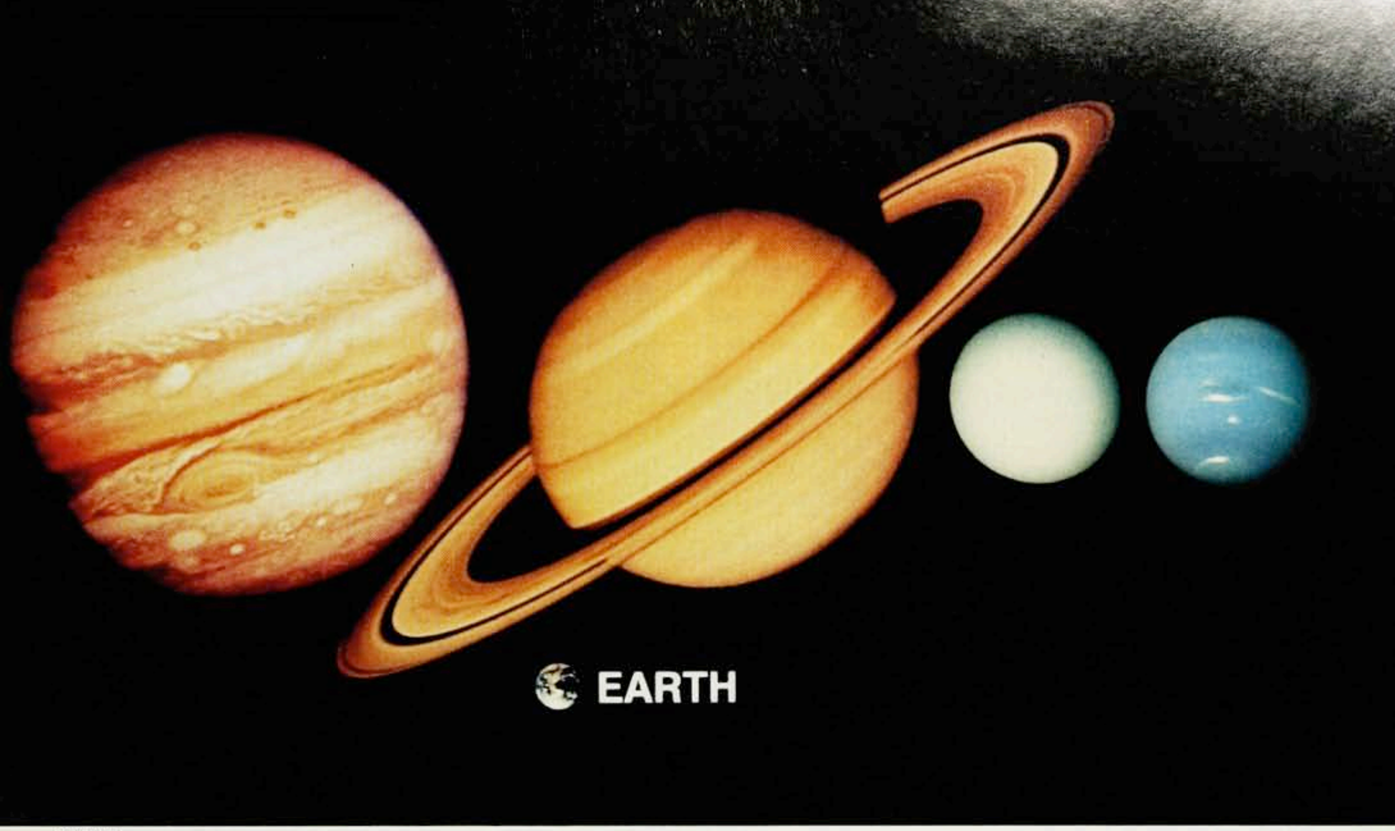
Learning to use Voyager

Before the two Voyager spacecraft could return their magnificent findings (described later in this article), project scientists had to overcome literally hundreds of unexpected problems. The vast majority were minor, and



NASA-JPL

Gas giants visited by the Voyager spacecraft, shown to scale with Earth. From left to right: Jupiter, Saturn, Uranus and Neptune. Methane gas in the atmospheres of Uranus and Neptune absorbs red from sunlight and is responsible for the blue color of those planets.

most were due to human error; such complex robotic machines required long periods of operation under a wide variety of conditions before project personnel could learn how to use their capabilities efficiently and safely. As each problem occurred, the causes were investigated and procedures and software were developed to prevent its recurrence or minimize its impact. Two potentially catastrophic problems on Voyager 2 are good examples. The first was the failure of the spacecraft's primary radio receiver; the second was the seizure of its steerable scan platform.

Receiver failure. Well before launch we realized that providing a backup receiver made no sense unless the spacecraft could somehow detect that its receiver had failed and switch to the alternate. Two of the six spacecraft computers were therefore programmed to reset an internal counter each time a command from Earth was received. If a (typically) seven-day period passed without command detection, Voyager was to assume that its primary receiver had failed and automatically revert to use of the backup.

When the immediate postlaunch flurry of activity ceased, the frequency of "real" commands to Voyager 2 slowed, and there was soon a period of seven days when no commands were required. Voyager engineers had forgotten about the receiver failure algorithm, and so command inactivity caused Voyager 2 to switch to its backup receiver. When we realized what had caused the problem, we transmitted commands to switch back to the primary receiver. However, during the switching, the primary receiver failed, possibly due to a momentary power surge. Another seven days passed before Voyager 2 again switched to its backup receiver, and it has operated on that unit ever since.

We soon discovered that a feedback mechanism in the backup receiver had failed. The receiver normally locks onto the frequency received from Earth, but Voyager 2's receiver would respond only to commands sent within a very narrow band of frequencies. The problem was traced to a shorted capacitor. The receiver frequency range was so narrow that the radio frequency of commands transmitted to Voyager 2 had to be adjusted to account for Doppler shifts due to the rotational and orbital motions of Earth as well as to the radial velocity of the spacecraft. To complicate matters, turning the spacecraft's instruments or heaters on or off would change the receiver's temperature and shift its sensitive frequency. The time required for the frequency to stabilize after power switching ranged up to 72 hours. While waiting for the engineers to again determine the "best lock frequency" of Voyager's tone-deaf receiver, we faced a moratorium on transmitting commands. In relatively short order, Voyager engineers and personnel at the Deep Space Network tracking stations devised methods for predicting and transmitting at the correct frequencies, and the faulty receiver did little to hinder data collection during any of the four planetary encounters.

Scan platform problems. Instrumentation for four of Voyager's 11 scientific investigations is mounted on an articulated platform with two degrees of freedom—azimuth and elevation. About 100 minutes after Voyager 2's closest approach to Saturn, during its passage through the planet's shadow, the platform seized in its azimuth axis and would not respond to further commands from its computers. After about an hour of no response, the spacecraft computers automatically turned off power to the platform motors. Extensive analysis has led us to conclude that the failure resulted from too frequent use of the scan platform at its highest rate, 1° per second. This drove lubricant from one of the motor gear shafts, and galling of the shaft material caused the seizure. Subsequent heating and cooling of the motor and gear train freed the platform sufficiently to permit us to point it at the receding planet about three days after closest approach, and at Saturn's outermost satellite, Phoebe, ten days after closest approach. Other than for a brief series of engineering tests, no platform motion was permitted for about 16 months thereafter. Since use of the platform resumed in February 1983, all slewing has been at rates of 0.083°/sec or slower, except for brief periods of medium-rate slewing (0.33°/sec) during near-encounter periods at Uranus and Neptune.

The spacecraft engineers also devised a method for checking whether the platform was beginning to experience excessive drag. In this procedure, known as torque margin testing, the duration of the motor drive pulses was reduced from the normal 200 msec to as low as 3 msec. The healthy actuators (as well as the Voyager 2 azimuth actuator) were found to drive at full rate with pulses of 6 msec or longer. Varying degrees of slowing were seen in all actuators with 5-msec pulses. Testing of identical actuators in the laboratory showed that when seizure was imminent, slowing occurred with pulse durations longer than 6 msec. Torque margin tests on both azimuth and elevation actuators on Voyagers 1 and 2 have shown that all four actuators are now healthy and in little danger of binding.

Another problem for Voyager 2 was both predictable and solvable. The spacecraft were initially designed only for encounters with Jupiter and Saturn. NASA later approved extention of the mission to allow Voyager 2 to go on to Uranus and Neptune. At the distance of Neptune, light levels are down by a factor of 900 from those at Earth's distance from the Sun. Voyager 2's computers were reprogrammed to permit longer imaging exposures, but image smear then became a problem. Smear in the recorded images was reduced by automatic attitude-jet firings to compensate for the torque caused by starting and stopping the tape recorder. The normal quiescent attitude-control angular rates were also slowed by reducing the jet pulses from 10 msec to 4 msec each. Methods were also devised to permit the cameras and other remote sensing instruments to track their targets more precisely, reducing image smear during times when the spacecraft was relatively close to its target.

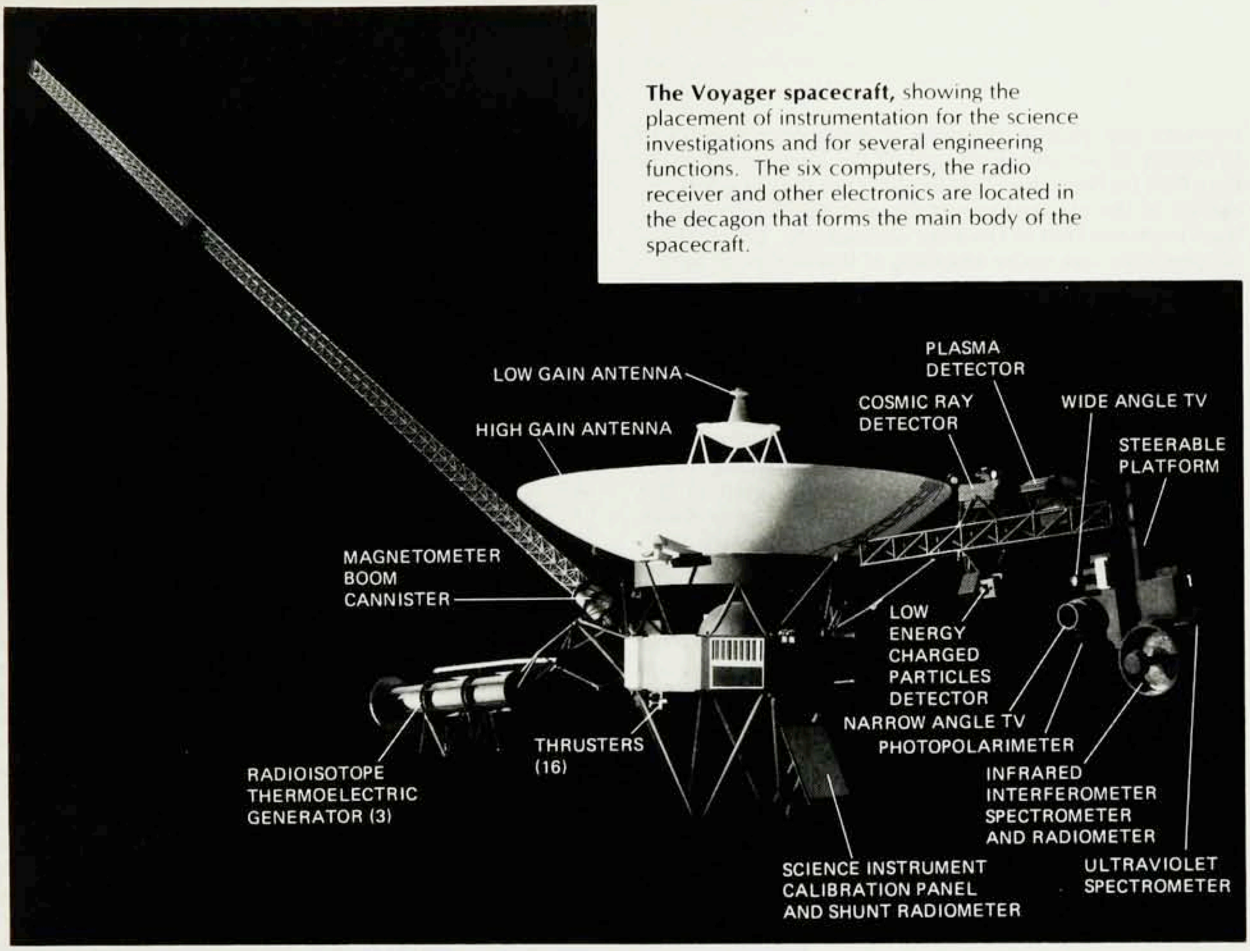
Scientific instrumentation

Each Voyager spacecraft carried instrumentation for 11 scientific investigations.[1] These included four remote sensing investigations, three charged-particle studies, magnetic field monitoring, plasma measurement and radio-wave detection. The 11th investigation, radio science, used Earth-based instrumentation to analyze changes in the radio signals between the time of their transmission from Voyager and their receipt at tracking stations in California, Australia or Spain. Some additional radio-science data was collected during the Neptune encounter by the Parkes radiotelescope in Australia and the Usuda tracking station in Japan; the Very Large Array in New Mexico assisted in collecting high-rate telemetry. Coordinated observations made it possible for the total science return from Voyager to exceed the sum of the results of the individual investigations.

The instruments for all 11 scientific investigations on Voyager 2 were still operating through the Neptune encounter. Voyager 1's photopolarimeter failed during the Jupiter encounter; its plasma instrument suffered a catastrophic loss of sensitivity shortly after the Saturn encounter. The other nine Voyager 1 investigations continued to function normally until after Voyager 2's encounter with Neptune. By early 1990 the imaging, photopolarimetry and infrared spectroscopy investigations had been permanently shut off on both spacecraft, and no more radio-science observations were being made. Ultraviolet stellar astronomy is continuing at a low level. Charged-particle, radio-wave and magnetic field investiga-

Voyager investigations and investigators

Investigation	Principal investigator (for which planets) and affiliation
Imaging	Bradford A. Smith (Jupiter, Saturn, Uranus, Neptune), University of Arizona, Tucson
Photopolarimetry	Charles F. Lillie (Jupiter—Voyager 1), Charles W. Hord (Jupiter—Voyager 2), University of Colorado, Boulder A. Lonne Lane (Saturn, Uranus, Neptune), JPL
Infrared spectroscopy	Rudolf A. Hanel (Jupiter, Saturn, Uranus), Barney J. Conrath (Neptune), Goddard Space Flight Center
Ultraviolet spectroscopy	A. Lyle Broadfoot (Jupiter, Saturn, Uranus, Neptune), University of Arizona, Tucson
Radio science	Von R. Eshleman (Jupiter), G. Leonard Tyler (Saturn, Uranus, Neptune), Stanford University
Magnetometry	Norman F. Ness (Jupiter, Saturn, Uranus, Neptune), Bartol Research Institute, University of Delaware, Newark
Plasma	Herbert S. Bridge (Jupiter, Saturn, Uranus), John W. Belcher (Neptune), Massachusetts Institute of Technology
Low-energy charged particles	Stamatios M. Krimigis (Jupiter, Saturn, Uranus, Neptune), Applied Physics Laboratory, Johns Hopkins University
Cosmic rays	Rochus E. Vogt (Jupiter, Saturn), Edward C. Stone (Uranus, Neptune), Caltech
Planetary radioastronomy	James W. Warwick (Jupiter, Saturn, Uranus, Neptune), Radiophysics Inc, Boulder, Colorado
Plasma waves	Frederick L. Scarf (deceased) (Jupiter, Saturn, Uranus), TRW Defense and Space Systems Group, Redondo Beach, California Donald A. Gurnett (Neptune), University of Iowa, Iowa City



The Voyager spacecraft, showing the placement of instrumentation for the science investigations and for several engineering functions. The six computers, the radio receiver and other electronics are located in the decagon that forms the main body of the spacecraft.

tions (except for the Voyager 1 plasma study) continue a search for the heliopause, the outer boundary of the Sun's magnetic field. We expect both Voyagers to collect useful data well into the 21st century.

Voyagers 1 and 2 encountered Jupiter on 5 March 1979 and 9 July 1979, respectively. Saturn encounters followed on 12 November 1980 and 25 August 1981. Voyager 2 continued on to encounter Uranus on 24 January 1986 and Neptune[2] on 25 August 1989. The Voyager Interstellar Mission, as it is officially named, began in early 1990.

Scientific findings

During the planetary encounters, data were gathered on:
▷ physical properties, dynamics and compositions of atmospheres
▷ thermal properties, total radiated energy and total energy absorbed from the Sun (the latter two for comparison)
▷ charged particles and electromagnetic environments
▷ ring systems
▷ satellite surface features
▷ periods of rotation, radii, shapes and other body properties
▷ masses and gravitational fields.

In the limited space available here it is not possible to present a comprehensive list of findings from the Voyager encounters. The results given below are but a brief summary of some of the major findings in the seven areas.

Atmospheres. The atmospheres of the four giant planets above their cloud tops are composed mostly of hydrogen and helium. For every 100 grams of atmospheric hydrogen, Jupiter has 18 ± 4 g of atmospheric helium, Saturn has 6 ± 5 g and Uranus has 26 ± 5 g. Analysis of the Neptune data is continuing, but it appears that the helium abundance in Neptune's atmosphere is equal to or greater than that of any of the other gas giant planets. When Voyager was launched, it was anticipated that the giant planets would probably have atmospheric compositions essentially identical to that of the early solar nebula. The Voyager data, however, show that even these giant bodies have undergone significant changes since their formation. The upper atmospheres of both Jupiter and Saturn have apparently been depleted of much of their original helium, presumably through gravitational settling of the heavier helium into the interiors of these planets. The upper atmospheres of Uranus and Neptune, on the other hand, seem to have somewhat larger fractions of helium than is estimated for the primordial solar nebula; it is possible that substantial amounts of hydrogen have escaped their lower gravitational fields.

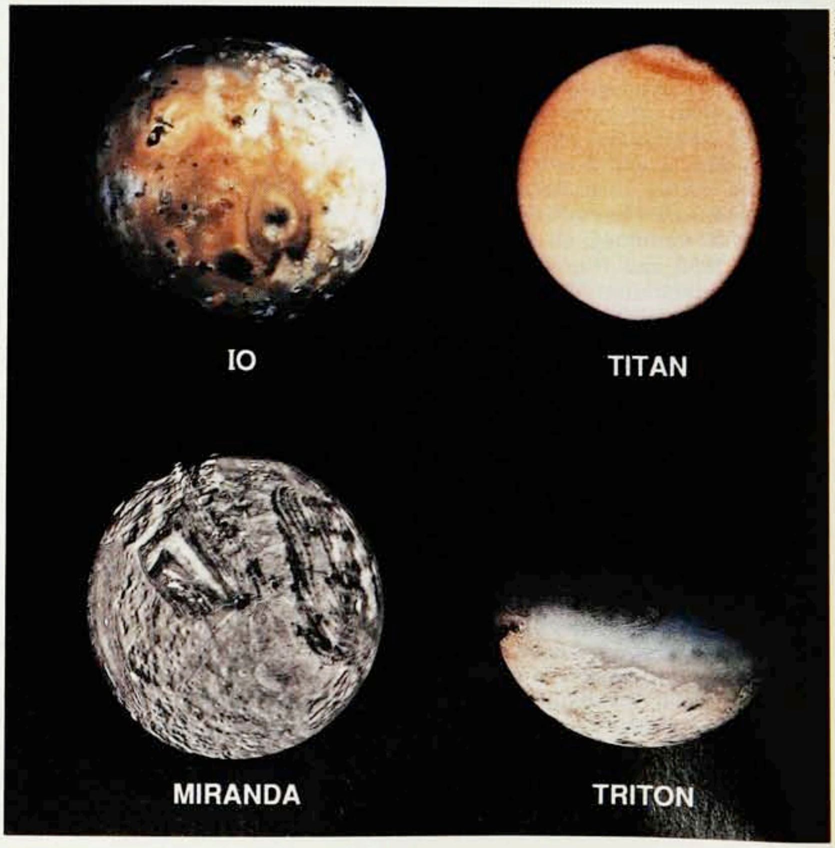
The visible clouds of Jupiter and Saturn are predominantly ammonia ice. Trace impurities give these clouds their colorations, such as the reddish tints of Jupiter's Great Red Spot, but their overall color closely replicates the yellow of the Sun. Methane is about ten times as abundant in the atmospheres of Uranus and Neptune as in the atmospheres of Jupiter and Saturn; the red-absorbing characteristics of methane gas give these planets their characteristic blue color. The uppermost clouds in the atmospheres of Uranus and Neptune are methane ice. Near the base of these clouds the molar fraction of methane gas (that is, the ratio of methane molecules to hydrogen molecules) is about 0.02 for Uranus and more than 0.01 for Neptune. This implies that the abundance of carbon in the atmospheres of Uranus and Neptune is at least ten times that in the solar atmosphere. Either these planets have lost major fractions of their original hydrogen and helium, or a much larger fraction of their total mass is the result of the capture of carbon-rich asteroids or comets than is the case for Jupiter or Saturn.

On each of the giant planets the atmosphere is organized into latitudinal zones that run parallel to the equator. These zones are most prominent on Jupiter and almost indistinguishable on Uranus. High-pressure anticyclonic oval storms are prominent in the atmospheres of Jupiter, Saturn and Neptune but are not seen in the atmosphere of Uranus. All these planets show a stable pattern of winds. On Jupiter, wind speeds vary with latitude, and wind directions shift from easterly (prograde) to westerly (retrograde) many times between the equator and poles. Saturn has a powerful prograde equatorial jet stream with wind speeds of up to 500 m/sec. Alternating prograde and retrograde winds poleward of 45° latitude display a north–south symmetry. Wind patterns on Uranus and Neptune are similar, with the strongest prograde winds near about 60° latitude and the strongest retrogrades near the equator. On Uranus, wind speeds vary from a prograde 200 m/sec near 60° latitude to a retrograde 100 m/sec near the equator. Winds on Neptune range from about 100 m/sec prograde near 70° south latitude to as much as 600 m/sec retrograde near the Great Dark Spot, at 20° south latitude. The precise processes that generate these strong winds are poorly understood, but the winds must be due in part to the manner in which each planet absorbs and redistributes heat from the Sun and from its own interior.

All four giant planets possess extended hydrogen atmospheres. The large scale heights imply extreme upper atmospheric temperatures—in excess of 1000 K for Jupiter, 600–800 K for Saturn and 750–800 K for Uranus and Neptune. In the case of Uranus, the nearness of the rings and the density of the atmosphere are sufficient to cause significant drag on ring particles. Ultraviolet emissions from sunlit portions of each atmosphere, termed "dayglow," may be related to the extended hydrogen atmospheres, but the source of the required energy is not well understood.

Two of the satellites have substantial atmospheres. Both Saturn's Titan and Neptune's Triton have atmospheres dominated by nitrogen and containing substantially smaller amounts of methane, but there the similarity ends. Thick layers of haze in Titan's atmosphere hide the surface in visible light; Triton's surface is unobscured. The near-surface atmospheric pressure on Titan is 1.6 bar; Triton's is only 1.6×10^{-5} bar. Much of that difference is a result of the different temperatures of these two satellites.

Thermal properties. The atmospheres of all of the giant planets have absolute temperature minima near the 0.1-bar pressure level. Jupiter's minimum temperature is about 110 K; Saturn's, 80 K; Uranus's, 52 K; and Neptune's, 50 K. Their respective effective temperatures (temperatures of a blackbody that would radiate the same amount of energy per unit area) are 124.4 K, 95.0 K, 59.1 K



Moons. Io, Titan, Miranda and Triton are the most interesting satellites of the planets shown in the figure on page 41. Jupiter's Io has active sulfurous volcanoes. Saturn's Titan possesses a thick, haze-filled nitrogen atmosphere. Uranus's Miranda displays some of the most bizarre geologic features seen in the solar system. Neptune's Triton has nitrogen ice caps, active geyser-like plumes and a tenuous nitrogen atmosphere.

Outer-planet data

	Earth	Jupiter	Saturn	Uranus	Neptune
Mean distance from Sun (10^9 km)	0.1496	0.7783	1.4294	2.8750	4.5043
Sidereal period of orbit (years)	1	11.8623	29.458	84.01	164.79
Mean orbital velocity (km/sec)	29.79	13.06	9.64	6.81	5.43
Orbital eccentricity	0.0167	0.0485	0.0556	0.0472	0.0086
Inclination to ecliptic (degrees)	0	1.30	2.49	0.77	1.77
Equatorial radius at 1 bar (km)	6378	71 492	60 268	25 559	24 764
Polar radius at 1 bar (km)	6357	66 854	54 364	24 973	24 340
Ellipticity of planet disk	0.00335	0.06487	0.09796	0.02293	0.0171
Volume of planet (Earth = 1)	1	1321.3	763.6	63.1	57.7
Mass of planet (Earth = 1)	1	317.892	95.184	14.536	17.148
Mean density (g/cm^3)	5.518	1.327	0.688	1.272	1.640
Body rotation period (hours)	23.9345	9.9249	10.6562	17.24	16.11
Tilt of equator to orbit (degrees)	23.45	3.08	26.73	97.92	28.8
Effective temperature (K)	287	124.4	95.0	59.1	59.3
Atmospheric temp. at 1 bar (K)	287	165 ± 5	134 ± 4	76 ± 2	74 ± 5
Number of observed satellites	1	16	20	15	8
Number of observed rings	0	1	7	10	4
Mean surface field (gauss)	0.308	4.28	0.218	0.228	0.133
Magnetic dipole tilt (degrees)	11.4	9.6	0.0	58.6	46.8
Magnetic dipole offset (planetary radii)	0.0725	—	0.04	0.3	0.55

and 59.3 K. Each of the planets, with the possible exception of Uranus, radiates more thermal energy than it receives from the Sun. The ratios of total radiated to total absorbed energy (also known as "energy balance") are 1.67 ± 0.08 for Jupiter, 1.79 ± 0.10 for Saturn, less than 1.14 for Uranus and 2.7 ± 0.3 for Neptune.

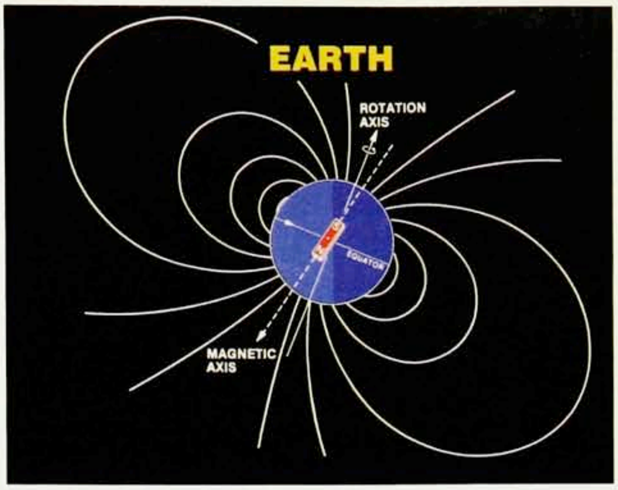
Triton's surface temperature of 38 ± 3 K makes it the coldest body measured by Voyager. Titan has a surface temperature of 95 ± 1 K. Jupiter's Io has typical subsolar (where the solar illumination is vertical) surface temperatures near 135 K, but hot spots associated with active volcanism can reach temperatures of 650 K or more. Jupiter's Europa, Ganymede and Callisto have typical subsolar surface temperatures near 125 K, 156 K and 168 K. Saturn's satellites Rhea, Tethys and Enceladus have subsolar surface temperatures of 100 ± 2 K, 93 ± 4 K and 75 ± 3 K, respectively. The temperature differences among the various satellites arise from differences in surface reflectivity and in distance from the Sun. The satellites with the highest reflectivities generally possess surfaces that have been altered in recent geologic time, most often as a result of processes that heat and partially melt materials near the surface.

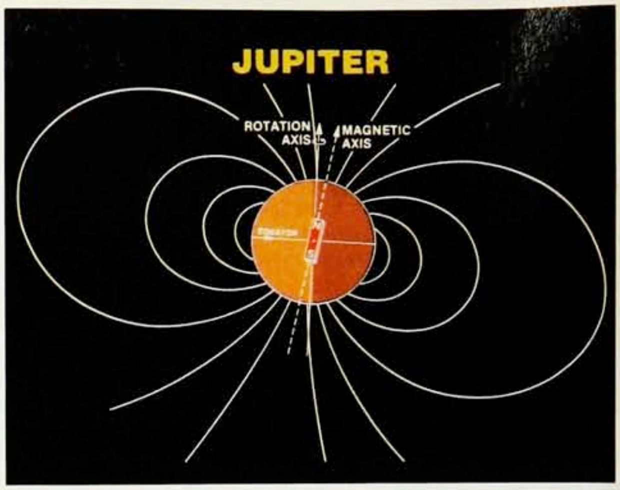
Electromagnetic environments. Each of the four giant planets possesses an intrinsic magnetic field and a trapped radiation field. Because the atmospheres rotate at different rates at different latitudes, periodic radio emissions (caused by the interaction between the planetary magnetic fields and the solar wind) are the best means for determining the body rotation period. Jupiter's rotation period has been found from Earth to be 9.9249 hours. Saturn, Uranus and Neptune were discovered by Voyager to complete one rotation in 10.6562, 17.24 and 16.11 hours, respectively. Both pulsed (like an omnidirectional strobe light) and beamed (like a rotating lighthouse light) radio emissions have been detected.

Saturn's magnetic field may be represented by a dipole magnet aligned with the planet's rotation axis but offset to the north by a distance of approximately 4% of the planet's radius. (See the figure on page 47 and the table above.) Jupiter's magnetic field is tilted by about 10° from the rotation axis. Electrical currents flow along the magnetic field lines connecting Jupiter and Io and in a current sheet around Jupiter's equator. Both flows distort the field sufficiently to make a simple offset dipolar magnetic field a poor representation of Jupiter's external field. Uranus and Neptune each have magnetic fields highly tilted with respect to their rotation axes and offset from their centers by large fractions of the planetary radii. These offsets possibly result from internal dynamos (circulating electrical currents) that are much closer to the cloudtops on Uranus and Neptune than they are on the nearby large planets or Earth. Perhaps the deeper parts of the cores of Uranus and Neptune are not efficient electrical conductors.

A torus of sulfur and oxygen ions surrounds Jupiter at the orbit of Io. This torus emits ultraviolet light, has temperatures of up to 100 000 K and is populated by more than 1000 electrons/cm^3. A "cold" plasma that corotates with the magnetic field exists between Io's orbit and the planet. It has larger than expected amounts of sulfur, sulfur dioxide and oxygen, all probably derived from Io's volcanic eruptions. The Sun-facing magnetopause (the outer edge of the magnetosphere) responds rapidly to changing solar wind pressure, varying from less than 50 Jovian radii to more than 100 Jovian radii in distance from the planet's center. A region of "hot" plasma that does not corotate with the planet lies in the outer magnetosphere. It consists primarily of hydrogen, oxygen and sulfur ions. About 25 Jovian radii behind the planet (that is, away from the Sun), the character of the magnetosphere changes from "closed" magnetic field lines to an extended magnetotail without line closure. This occurs as a result of downstream interaction with the solar wind. Jupiter's magnetotail probably extends to, and perhaps goes beyond, the orbit of Saturn, more than 700 million kilometers "downwind" from Jupiter.

The magnetospheres of the other three giant planets are smaller structures with similar but less extreme characteristics. As one goes further from the Sun, each is less populated with charged particles than its predecessor, and each is influenced less by the satellites that orbit within it. Voyager saw both visible and ultraviolet emissions in the nightside polar atmosphere of Jupiter. Lightning superbolts were also seen in images of Jupiter's unilluminated face. Radio emissions from lightning were detected at both Jupiter and Saturn, but not at Uranus or Neptune. Jupiter's Io and Saturn's Titan may contribute





major fractions of the charged particles within the magnetospheres of their planets. Uranus and Neptune have no such sources.

The spacecraft have also detected charged particles, magnetic fields and radio emissions between and beyond the planets. Both Voyagers have been monitoring these interplanetary characteristics continuously since shortly after launch and have provided much useful information about that environment. Tracking coverage by the Deep Space Network antennas has permitted daily monitoring of the continuously transmitted data.

Ring systems. Until five months before the 1977 launches of Voyagers 1 and 2, Saturn was the only planet known to have rings. Now Voyager 2 has relayed detailed data about ring systems around all of the giant planets. Each system is found to have unique characteristics: Jupiter's faint ring is composed primarily of tiny dust particles, probably the result of meteoroid bombardment of the satellites Metis and Adrastea. Saturn's ring has far more detail than had been supposed prior to Voyager; it is very bright, is composed mainly of water ice, has a wide distribution of particle sizes and forms an extensive sheet of material closely confined to Saturn's equatorial plane. Self-gravity and the gravitational effects of nearby satellites combine to create a wonderfully complex structure including tightly wound spiral formations, gaps, narrow ringlets and sharp ring edges. Microscopic particles interact with Saturn's magnetic field to create radial spokes that appear suddenly in the outer portions of the B ring, rotate at the speed of the magnetic field and then slowly dissipate.

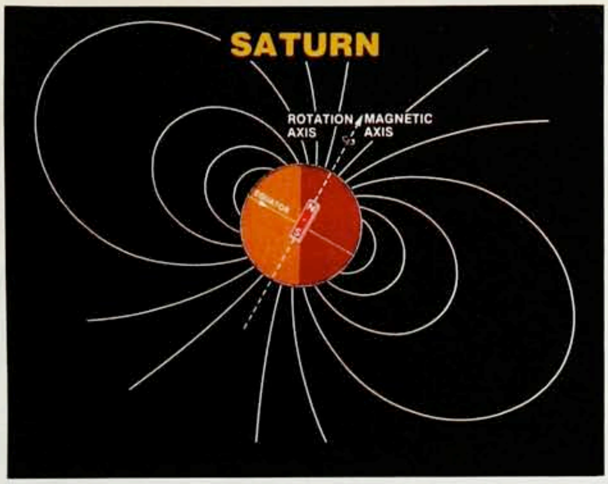
The Uranus and Neptune ring systems consist primarily of series of narrow rings, most likely constrained from spreading by the gravitational action of both seen and unseen satellites. The extremely dark color of these ring systems either is a result of coating by carbonaceous material or is due to the action of high-energy protons on methane trapped in the ice in the particles. The rings of Uranus are dominated by macroscopic particles; the Neptune ring system has a larger proportion of dust-sized particles. Strong azimuthal concentrations of ring particles apparent in Neptune's outer ring, which were first detected from Earth, led to the suggestion that Neptune possessed only partial rings. These arc-like segments within the unbroken ring would normally be expected to spread to azimuthal uniformity within a few years or less; it is therefore likely that unseen bodies or unknown processes confine the arcs and prevent their spreading.

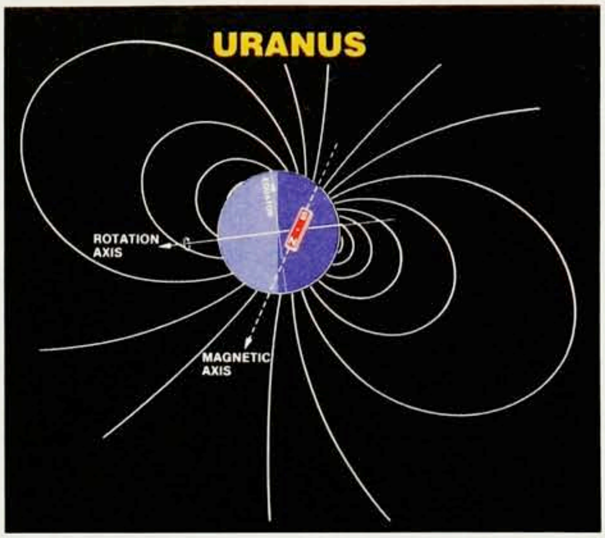
An unexpected outcome of the Voyager findings is the realization that planetary rings are apparently rapidly evolving structures. Their complex interactions include self-gravity effects, magnetic field interactions and atmospheric drag, in addition to "shepherding" by nearby satellites. It now appears likely that a continual process of breakup of larger bodies into progressively smaller bodies is inherent in the creation and maintenance of ring systems.

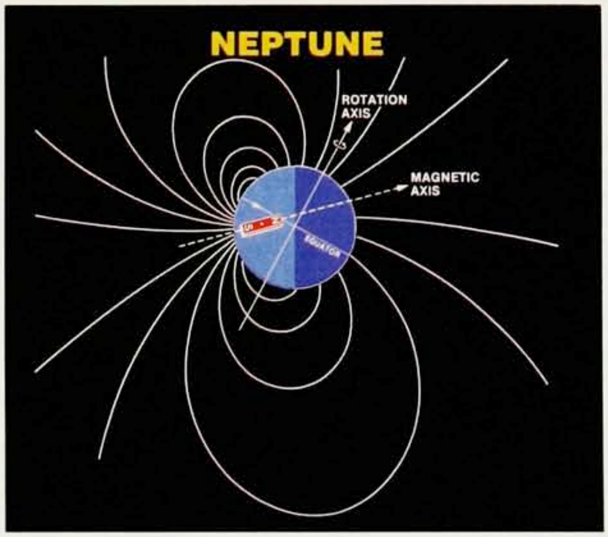
Satellite surfaces. Voyagers 1 and 2 were responsible for discovering at least 21 new satellites, for determining of the sizes of all but 12 of the solar system's 60 known satellites and for taking the only detailed images of the surfaces of the satellites of the giant planets. Surface maps from Voyager data now exist for Jupiter's Amalthea, Io, Europa, Ganymede and Callisto; for Saturn's Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion and Iapetus; for Uranus's Puck, Miranda, Ariel, Umbriel, Titania and Oberon; and for Neptune's Triton. Ancient cratered surfaces were expected on all the satellites, but Voyager has also disclosed an enormous variety of unexpected surface features. These range from active volcanism (on Io and Triton) to evidence for flows of crustal materials (on Ganymede, Enceladus, Ariel and others) to unexplained landforms (on Miranda and others) to haze-enshrouded lakes of liquid ethane (on Titan). It is obvious that many processes due to internally generated heat have occurred since the early cratering epochs to alter the surfaces of these satellites.

Body properties. Most of the satellites in the solar system are in locked rotation, keeping one face toward their respective planets at all times. Noteworthy exceptions are Jupiter's outer eight satellites, Saturn's Hyperion and Phoebe, and probably Neptune's Nereid. Jupiter's outer eight are all thought to be captured asteroids; Voyager did not study them. Phoebe makes a full rotation in approximately 9 hours and orbits Saturn with a period of 550 days. Hyperion tumbles chaotically due to frequent gravitational interactions with nearby Titan. Voyager did not detect Nereid's rotation, but this satellite's highly elliptical orbit makes it an unlikely candidate for synchronous rotation.

Voyager found several satellites to be significantly nonspherical. These include Adrastea, Amalthea and Thebe at Jupiter; Atlas, Prometheus, Pandora, Epimetheus, Janus, Telesto, Calypso, Helene and Hyperion at Saturn; and 1989N1 and 1989N2 at Neptune. Voyager also measured differences between equatorial and polar radii for several other satellites and for the four planets. Surface reflectivities of the satellites range from almost







Magnetic fields of the four giant planets and Earth, represented by bar magnets within each planet. Only in Uranus and Neptune are the magnetic axes grossly misaligned with the rotation axes. Note also the offsets of the magnetic fields from the centers of the planets.

100% (Enceladus) to about 5% (Metis, Adrastea, Amalthea, Thebe, Phoebe and the dark face of Iapetus). The highly reflective surfaces are a result of recent geologic activity; the darkest surfaces probably represent carbon-bearing compounds or elemental carbon, either deposited by infall or created by the irradiation-induced decomposition of methane ices.

Bulk properties. The masses of the four planets were already known to reasonable accuracy from Earth-based observations. Voyager refined the densities, primarily by providing better estimates of sizes and shapes. Our knowledge of internal mass distributions was also improved by measuring body rotation periods and nonspherical gravity forces on the spacecraft. Models in vogue prior to Voyager are now seen to show Uranus and Neptune as too centrally condensed. Voyager tracking data lead to the conclusion that much larger percentages of the planetary mass lie well away from the centers of the planets than was expected.

Voyager data allowed determination of the masses and densities of 17 satellites. Saturn's satellites all appear to have densities between 1.1 and 1.5 g/cm^3, except for Titan, whose density is 1.88 g/cm^3. Neptune's Triton is 2.05 g/cm^3 in density. Uranus's four largest satellites range from 1.5 to 1.7 g/cm^3. These low densities all indicate large amounts of water ice. Jupiter's satellites, by contrast, range in density from 1.86 g/cm^3 for Callisto (the outermost of the Galilean satellites) to 3.55 g/cm^3 for Io (the innermost of the Galilean satellites). This wide variation implies that heat from Jupiter in its formative stages was sufficient to drive water from its inner satellites.

To the heliopause and beyond

The two Voyager spacecraft were designed to have a high probability of surviving the four years between launch and Voyager 2's Saturn encounter. After nearly 13 years of continuous operation they continue to function well and to collect useful scientific data about the outer solar system environment. Barring unforeseen catastrophic failures, the power, propellant and communication link resources should keep both spacecraft collecting field, particle and wave data until at least the year 2015. By then both Voyager 1 and Voyager 2 will be more than three times the distance of Neptune (and Pluto) from the Sun; their respective outward velocities will be 16.6 and 14.9 km/sec. The Sun's magnetic field and the solar wind are believed not to extend to those great distances, and so the Voyagers may become the first man-made spacecraft to exit the "heliosphere" and make *in situ* measurements of the interstellar environment. Such measurements would represent still another in a long line of firsts for the highly successful Voyager mission.

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Voyager is one of the programs of the Solar System Exploration Division of NASA's Office of Space Science and Applications. The Voyager project is managed by the Jet Propulsion Laboratory of the California Institute of Technology under contract with NASA.

References

1. For detailed descriptions of the 11 scientific investigations, see Space Sci. Rev. **21**, 103 (1977).
2. For a description of Voyager 2's Neptune encounter and preliminary results, see Science **246**, 1417 (1989); page 1421 has references to detailed Voyager findings at Jupiter, Saturn and Uranus. ■