ter. Commitment to a Saturn-bound trajectory was withheld until the complete success of Pioneer 10 eliminated the need for a repetition of the first flyby.

Pioneer 11 spiraled tightly around Jupiter, approaching from the south in front of Jupiter's orbital path and departing northward and back toward the sun. The trajectory across the solar system was inclined 15° above the ecliptic plane, with perihelion at 3.5 astronomical units.

The error projected at Saturn was about 2 million kilometers, little more than the predicted probable error. Time of projected arrival at Saturn was 3 September 1979, only 8 days before superior conjunction with Earth. The adjustment of the time of arrival to 1 September was designed to avoid solar interference at encounter as much as the available propellant would allow. The largest maneuvers, totaling 47 m/sec, were executed near perihelion in December 1975 and May 1976. The final maneuver to the target was completed in July 1978. The exact time of flyby was chosen to center the DSN's largest overlapping view, between the Canberra and Madrid Deep Space Stations, on Saturn.

Options for the spacecraft to fly by Saturn either inside or outside the visible rings were retained until late 1977. The outside was chosen because the expected scientific return at Saturn would be close to the optimum, the survival probability was very much greater, and penetration of the ring plane at the same radius necessary for the hoped-for continuation of Voyager 2 to Uranus could be directly tested. Pioneer Saturn penetrated Saturn's equatorial plane inbound at 2.82 Saturn radii (R_S) and outbound at 2.78 R_S without observable incident (Fig. 2).

Descent from above the ecliptic plane toward Saturn late in the morning quadrant gave Pioneer a view of the dark side of the rings. The approach asymptote was 6° above, while sunlight came from 2° below, the plane of the rings. Studies of the magnetosphere and its interaction with the solar wind, mapping of infrared radiation, and analyses of the radio signal for gravitational and atmospheric effects were well served by the chosen trajectory (Fig. 3). Only the ultraviolet radiometer was not in a position to observe Saturn satisfactorily, from a safe distance outside the anticipated trapped radiation. Therefore, to gather data in the ultraviolet, the spacecraft's spin axis was maneuvered as far as practical ($1^1/_4°$) away from Earth pointing for days 15 through 11 before encounter, and its data rate was temporarily reduced.

Solar noise became an important constraint at Saturn encounter. Plans to gather data for a few hours at 1024 bits per second from two of the tracking stations at their highest elevations had to be abandoned. Rapid reductions below 512 bits per second were forced by solar noise, beginning only 2 days after encounter.

The spacecraft departed from Saturn only slightly above the ring plane, and nearly along the morning terminator where polarimetry could be performed at a large solar phase angle. Titan's orbit was crossed 25 hours after Saturn flyby, affording a distant exposure (363,000 km) to the three remote sensing instruments.

Pioneer 11 became the second spacecraft to escape the solar system on its swing past Saturn. Departure asymptote from the sun is 251° celestial longitude and 12.6° above the ecliptic plane. Near the direction of the solar apex (that is, the direction of the sun's motion relative to its galactic neighbors), Pioneer 11's departure is roughly opposite Pioneer 10's trajectory.

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References

1. *Science* **183**, 301 (1974); *ibid.* **188**, 445 (1975).

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Scientific Results from the Pioneer Saturn Encounter: Summary

Abstract. *An overview of the Pioneer encounter with Saturn is presented, including a brief discussion of the characteristics of the planet and a summary of the scientific results, which are described in detail in the following reports.*

The objective of the Pioneer encounter with Saturn was to image the planet, its rings, and its satellites; to measure its particulate environment; and to measure the magnetic field and the photon and charged particle radiation associated with the Saturn system. Eleven operating scientific instruments were carried on Pioneer to meet these objectives. In addition, the 2.293-GHz telemetry carrier signal was used to study variations in the gravitational field of the Saturn system to better understand the distribution of matter in and around Saturn, and to understand the atmosphere and ionosphere by means of radio occultation

Table 1. Pioneer Saturn scientific instruments.

Instrument	Principal investigator	Experiment objective
Helium vector magnetometer	E. J. Smith, Jet Propulsion Laboratory	Magnetic fields
Fluxgate magnetometer	M. H. Acuna, Goddard Space Flight Center	Magnetic fields
Plasma analyzer	J. H. Wolfe, Ames Research Center	Solar plasma
Charged particle	J. A. Simpson, University of Chicago	Charged particle composition
Cosmic-ray telescope	F. B. McDonald, Goddard Space Flight Center	Cosmic-ray energy spectra
Geiger tube telescope	J. A. Van Allen, University of Iowa	Charged particles
Trapped radiation detector	W. Fillius, University of California, San Diego	Trapped radiation
Asteroid-meteoroid detector*	R. K. Soberman General Electric Co. and Drexel University	Asteroid-meteoroid astronomy
Meteoroid detector	W. H. Kinard Langley Research Center	Meteoroid detection
Radio transmitter and Deep Space Network	J. D. Anderson, Jet Propulsion Laboratory	Celestial mechanics
Ultraviolet photometer	D. L. Judge, University of Southern California, Los Angeles	Ultraviolet photometry
Imaging photopolarimeter	T. Gehrels, University of Arizona, Tucson	Photo imaging and polarimetry
Infrared radiometer	A. P. Ingersoll California Institute of Technology	Infrared thermal structure
Radio transmitter and Deep Space Network	A. J. Kliore, Jet Propulsion Laboratory	S-band occultation

*Not currently operational.

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Table 2. Earth, Jupiter, and Saturn comparison table.

Parameter	Earth	Jupiter	Saturn
Equatorial radius (km)	6,378	71,400	60,000
Satellites	1	14	11 (?)
Year	1	11.86	29.46
Day	$23^h 56^m 04^s$	$9^h 55^m 30^s$	$10^h 14^m$
Mass	1	317.9	95.2
Density (g cm^{-3})	5.5	1.3	0.7
Mean distance from sun (AU)	1	5.2	9.5
Magnetic moment (gauss-cm^3)	8.1×10^{25}	14.6×10^{29}	4.3×10^{28}
Mean distance to magneto-spheric subsolar point	$10 R_E$	$100 R_J$	$30 R_S$

measurements. Table 1 lists the Pioneer Saturn investigations and their principal investigators. This report summarizes the scientific results from the Pioneer encounter with Saturn. The information presented here was drawn largely from the following 13 reports by the scientific participants in the Pioneer mission.

Saturn is the second largest planet in the solar system. It has a radius of 60,000 km (hereafter designated 1 R_S) and a density of about 0.7 g cm^{-3}. The planet rotates with a period of 10 hours and 14 minutes; and it revolves around the sun with a period of 29.46 years. Table 2 compares the general characteristics of Saturn with those of Earth and Jupiter, and Table 3 lists the satellites of Saturn. The rings of Saturn are listed in table 2 of the report by Gehrels *et al.* (*1*).

Rings, satellites, and planet. One of the major scientific contributions from Pioneer was a better overall understanding of the rings of Saturn. Before the Pioneer encounter, five rings had been tentatively identified. From the planet outward, they are D, C, B, A, and E. No evidence was found for the D ring in the Pioneer images. Similarly, the E ring was not visible in the images; but its presence may have been detected in the charged particle data. The micrometeoroid detector registered two particle hits 900 km above the plane of the E ring. If these are ring particles, the E ring is at least 1800 km thick. Its optical depth is of the order 10^{-8}, compared to 0.1 to 1 for the A, B, and C rings. A new ring, named the F ring, was discovered immediately beyond the A ring. The F ring is a narrow feature, less than 800 km wide, located at 2.33 R_S. It is separated from the A ring by a 3600-km-wide gap referred to as the Pioneer division. The celestial mechanics and ultraviolet photometer data show that the rings have a mass of less than 3×10^{-6} planet masses, and they are encircled by a cloud of atomic hydrogen. These observations establish that the rings are made up of low-mass materials, such as ices of H_2O and NH_3. The nonuniform distribution of the ultraviolet emission along the rings shows a nonuniform clumping of material in the B ring. The rings have a temperature of 60 to 70 K on the illuminated side and about 55 K on the unilluminated side. This implies very little thermal contact or cross-plane motion by the ring particles.

The imaging photopolarimeter (IPP) and the charged particle instruments detected a previously unidentified satellite of Saturn at 2.53 ± 0.01 R_S. The object is identified as 1979 S 1—that is, the first satellite of Saturn discovered in 1979. It is possible that this object is also satellite S 11, previously identified by Fountain and Larson (*2*) from ground-based observations. The diameter of 1979 S 1 is estimated to be about 200 km. Other objects have been detected from charged particle absorption features during the encounter. These have not been observed by the IPP and their visual confirmation must therefore await the arrival of Voyager 1 at Saturn in November 1980. The masses of Rhea and Iapetus, which were previously unknown, have been determined as $21.4 \pm 7 \times 10^{23}$ and $28 \pm 7 \times 10^{23}$ g, corresponding to densities of 1.0 ± 0.5 g cm^{-3} for Rhea and 1.8 ± 0.5 g cm^{-3} for Iapetus. Pioneer passed within only 356,000 km of Titan. Consequently, data on that satellite are sketchy. The infrared radiometer recorded a disk brightness temperature at Titan of 80 ± 10 K. A cloud of hydrogen was found around Titan, extending about 5 R_S away from it, and evidence for the wake of Titan within the corotating Saturn magnetosphere was tentatively detected in the magnetic field data.

The radius of Saturn was confirmed to be 60,000 ± 500 km, with a polar flattening of about 5280 km. Images of Saturn showed very little detail. There is some evidence for a jet stream near the equator and also just below the North Polar Region. The effective temperature of Saturn is 94.4 ± 3 K. The ratio of the total planetary emission to absorbed sunlight is 2.2 ± 0.7, corresponding to an internal heat flux of 2.4 ± 0.8 W m^{-2}. These figures assume an albedo of 0.45 ± 0.15. A heat flux of this magnitude is higher than that derived from cooling-history models, and it suggests an additional internal energy source such as gravitational separation of hydrogen and helium. The infrared data also suggest that Saturn's clouds are thicker than the cloud layer of Jupiter. The radio occultation observations of Saturn have identified a thin ionosphere with two peaks in electron density; the highest is 9.4×10^3 cm^{-3} at 2800 km, and the second is 7×10^3 cm^{-3} at 2200 km. The atmospheric temperature results derived from the radio occultation data are consistent with the infrared results and imply an atmospheric helium abundance about one-half the solar value.

The presence of a magnetic field in Saturn had been suspected since 1975 (*3, 4*). The magnetic field measured by Pioneer has an equatorial value of 0.2 gauss, corresponding to a magnetic moment of 4.3×10^{28} gauss-cm^3. This is a factor of 5 smaller than predicted from models, but it is consistent with radio observations. The polarity of the field is the same as at Jupiter; that is, opposite to the polarity of Earth's field. The field is largely dipolar, but a surprising discovery of Pioneer is that the dipole axis of the field is tilted less than 1° to the rotational axis of Saturn. This is compared to the 10° to 20° tilts for Earth and Jupiter. The very

Table 3. Satellites of Saturn.

Name	Diameter (km)	Semimajor axis	
		km	R_S
1979 S 1 (S 11?)	200 (estimated)	151,800	2.53
Janus	200 (estimated)	168,700	2.81
Mimas	944	185,800	3.10
Enceladus	600	238,300	3.97
Tethys	1,040	294,900	4.92
Dione	1,000	377,900	6.30
Rhea	1,600	527,600	8.79
Titan	5,800	1,222,600	20.38
Hyperion	225 (estimated)	1,484,100	24.74
Iapetus	1,450	3,562,900	59.38
Phoebe (retrograde)	240 (estimated)	12,960,000	216

small tilt makes it difficult to explain the origin of the field in terms of classical dynamo theory (5). The absence of tilt coupled with the lack of surface detail also makes it difficult to determine an exact rotational period for Saturn. The magnetic field measurements and the celestial mechanics results are consistent with a model for the interior of Saturn that has a small inner core of about 0.2 R_S, consisting of rocky material such as MgO, SiO_2, FeS, and FeO, surrounded by an outer core of metallic hydrogen extending from 0.2 to 0.5 R_S, and that in turn surrounded by a liquid hydrogen-helium outer envelope. The 0.5-R_S core is considerably smaller than the 0.75-R_J (1 R_J = 71,400 km) core at Jupiter.

Magnetosphere. The magnetic field of Saturn has created a magnetosphere intermediate in size between the magnetospheres of Earth and Jupiter. The bow shock wave was first encountered near 24 R_S. The bow shock was again crossed at 23.1 and at 19.9 R_S before the magnetopause was crossed at 17.3 R_S. Solar activity in late August increased the solar wind pressure on the magnetic field, resulting in compression of the magnetosphere to less than its quiet time standoff distance. Pioneer entered the magnetosphere near the noon meridian and exited along the dawn meridian. The effects of the solar disturbance had largely passed by the time Pioneer exited the magnetosphere. As a consequence, magnetospheric boundaries were moving much more rapidly than they do during periods of high solar wind pressure. On the outbound leg, the magnetopause was crossed five times between 30.25 and 39.81 R_S and the bow shock was crossed nine times between 49.26 and 102 R_S.

The magnetosphere itself can be divided into four parts: the outer magnetosphere, the slot, the inner magnetosphere, and the rings. The outer magnetosphere contained, at the time of the encounter, an inflated corotating plasma. The ions O^+ or OH^+ have been tentatively identified. This is a strong indication that the low-energy particles originated from dissociated ring material rather than from the penetration of solar wind ions into the magnetosphere. Low-energy trapped charged particles were found inside 17 R_S and extended inward to about 7.5 R_S. The outer magnetosphere is characterized by large, time-varying fluxes of trapped particles, with large variations in their angular distribution. During the outbound leg beyond 8 R_S a chaotic particle distribution and a rapidly changing magnetic field polarity was encountered. This has been attributed to the development of an equatorial current sheet or the detection of a magnetospheric tail current sheet. The outer magnetosphere is terminated sharply at 7.5 R_S by a sudden drop in both the proton and electron fluxes. The slot region resulting from the reduction in particle flux is attributable to strong particle absorption by the satellites Dione, Tethys, and Enceladus. The slot extends in to 4 R_S. The charged particle data contain evidence that plasma processes, as well as satellite absorption, are sweeping charged particles out of the magnetosphere in the slot region.

Inside 4 R_S, particle fluxes and energies increase and the spectra become much harder and more complex. Maximum flux for protons with energies greater than 35 MeV is 3×10^4 cm^{-2} sec^{-1} and for electrons with energies greater than 3.4 MeV is 3×10^6 cm^{-2} sec^{-1}. The charged particles trapped in the inner magnetosphere show strong symmetry between the inbound and outbound legs of the encounter. This is a direct consequence of the coincidence of the magnetic axis with the rotational axis of the planet. A distinct absorption feature in the particle fluxes was found associated with the satellite Mimas at 3.1 R_S. Particle absorption features were also used to discover one and possibly more previously known Saturn satellites and to place an upper limit on the diffusion coefficient for trapped particles in that region of the magnetosphere. The magnetospheric environment of the rings is characterized by the virtually complete absence of any charged particle radiation. Inside 2.3 R_S, the outer edge of the A ring, there is a nearly complete dropout of particles. Searches for the photon radiation resulting from the high-energy particle absorption have yielded negative results.

Summary. The spacecraft and instruments all survived passage through the rings of Saturn. Pioneer established that subsequent missions to the outer planets, such as those of Voyager 1 and Voyager 2, will be able to survive an outside crossing of the Saturn rings as well as the trapped radiation environments. Pioneer Saturn continues to provide scientific data on the interplanetary medium. The spacecraft is presently traveling in the direction of the apex of the solar wind interaction with the interstellar medium. Spacecraft power and tracking capability are adequate to continue data acquisition into the middle 1980's.

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References

1. T. Gehrels *et al.*, *Science* **207**, 434 (1980).
2. J. W. Fountain and S. M. Larson, *Icarus* **36**, 92 (1978).
3. L. W. Brown, *Astrophys. J.* **198**, L89 (1975).
4. M. L. Kaiser and R. G. Stone, *Science* **189**, 285 (1975).
5. T. G. Cowling, *Magnetohydrodynamics* (Interscience, New York, 1957), p. 78.

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Preliminary Results on the Plasma Environment of Saturn from the Pioneer 11 Plasma Analyzer Experiment

Abstract. *The Ames Research Center Pioneer 11 plasma analyzer experiment provided measurements of the solar wind interaction with Saturn and the character of the plasma environment within Saturn's magnetosphere. It is shown that Saturn has a detached bow shock wave and magnetopause quite similar to those at Earth and Jupiter. The scale size of the interaction region for Saturn is roughly one-third that at Jupiter, but Saturn's magnetosphere is equally responsive to changes in the solar wind dynamic pressure. Saturn's outer magnetosphere is inflated, as evidenced by the observation of large fluxes of corotating plasma. It is postulated that Saturn's magnetosphere may undergo a large expansion when the solar wind pressure is greatly diminished by the presence of Jupiter's extended magnetospheric tail when the two planets are approximately aligned along the same solar radial vector.*

The Pioneer 11 spacecraft, launched on 6 April 1973, passed at a distance of 1.35 R_S (Saturn radii; 1 R_S = 60,000 km) from the center of the planet at 1631 UT (spacecraft time) on 1 September 1979. The Ames Research Center plasma analyzer experiment on Pioneer 11, identical to that on Pioneer 10 (*1*), utilizes dual, 90°, quadrispherical electrostatic analyzers for measurements of the energy and direction of motion of the charged particles that comprise the incident plasma. The experiment includes a medium-resolution analyzer that incorporates five current collectors and attendant electrometer amplifiers for charged particle detection, and a high-resolution analyzer that has 26 Bendix-type CEM 4012 detectors operated in the pulse counting mode. The plasma analyzer ex-

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