Reports

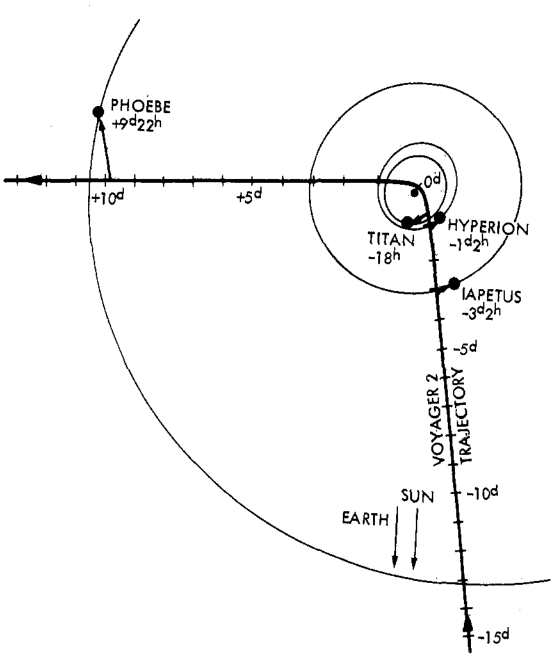
Voyager 2 Encounter with the Saturnian System

Abstract. *An overview of the Voyager 2 encounter with Saturn is presented, including a brief discussion of the trajectory, the planned observations, and highlights of the results described in the subsequent reports.*

With the successful accomplishment of its encounter with Saturn, Voyager 2 completed the fourth step in the NASA Voyager program of exploration of the outer planets, which began with the launch of Voyager 2 from Cape Canaveral, Florida, on 20 August 1977 (*1*). Prior to the closest approach of Voyager 2 to Saturn on 26 August 1981, both Voyager 1 and Voyager 2 had completed successful encounters of Jupiter, with closest approaches occurring on 5 March 1979 and 9 July 1979, respectively (*2*), and Voyager 1 had preceded its twin through the Saturn system, with its closest approach on 12 November 1980 (*3, 4*). The Voyager 2 encounter occurred almost exactly 2 years after the Pioneer 11 encounter on 1 September 1979 (*5*). This and the following reports summarize the preliminary findings from the scientific investigations conducted during the Voyager 2 passage through the Saturn system.

In order to use a gravity boost at Saturn to propel Voyager 2 on toward a 1986 encounter with Uranus, it was necessary for the spacecraft to arrive at Saturn considerably later than Voyager 1 so that Uranus and Saturn were suitably positioned. As a result, the Voyager 2 flight time to Saturn was just over 48 months and the flight distance almost 2.3 billion kilometers (1.4 billion miles). Voyager 1, on the other hand, completed that portion of its journey in just over 38 months. The slower pace of Voyager 2 permitted a somewhat more leisurely scientific investigation of the interplanetary environment between Jupiter and Saturn and of the Saturn system itself.

The Voyager 2 scientific investigations and principal investigators are identical to those listed for Voyager 1 (*3*). All instruments, including the Voyager 2 photopolarimeter, functioned nominally during the Voyager 2 encounter of Saturn. Two anomalies during the encounter did affect the acquisition of data, however. The most serious was a temporary cessation of operation of the science instrument scan platform, which points the imaging cameras, photopolarimeter, and infrared and ultraviolet spectrometers. The problem occurred about 110 minutes after Saturn closest approach, while the spacecraft was passing through Saturn's shadow and out of communication with the earth. During the period from Saturn closest approach until almost 5 hours after closest approach, the attitude of the spacecraft was referenced to internal gyroscopes. Because of a gyroscope calibration error, the space-



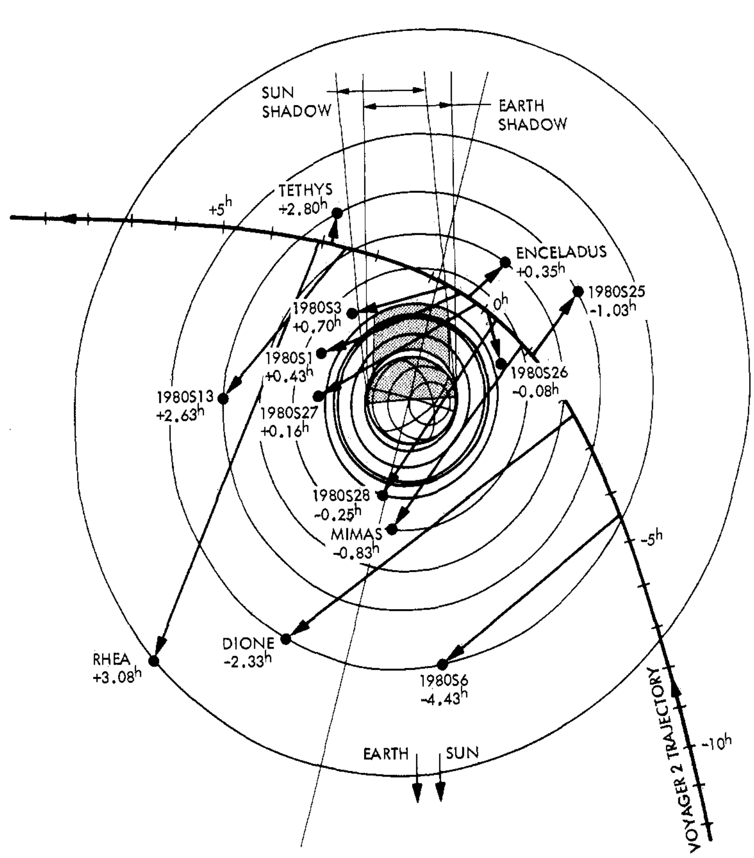


Fig. 1 (left). Voyager 2 path through the Saturn system shown in the plane of the spacecraft trajectory. The projected orbits of Phoebe, Iapetus, Hyperion, and Titan are shown along with the positions of these satellites at the times (labeled) when Voyager 2 was closest to them. Time ticks along the trajectory mark Voyager's position at 1-day intervals. Fig. 2 (right). Voyager 2 path through the orbits of the inner satellites of Saturn. The orbits of Mimas through Rhea are shown projected into the plane of the spacecraft trajectory. Positions of all of the satellites are shown at the times (labeled) when Voyager 2 was closest to them. The limits in the plane of the spacecraft trajectory of the sun and Earth "shadows" are shown. Time ticks mark Voyager's position at 1-hour intervals.

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craft maneuvers resulted in a roll attitude offset of about 1°, which persisted until celestial references were reacquired. This attitude offset was too small to adversely affect radio science or wide-angle imaging observations, but infrared and narrow-angle imaging observations of the satellites were pointed just off the edge of their targets. Fortunately, most of the critical Voyager 2 observations had been completed before these anomalies occurred; lost were some close-approach observations of Enceladus and Tethys, some dark-side ring observations, and much of the southern hemisphere atmospheric high-resolution studies. Partial operation of the scan platform was restored about 2.8 days after closest approach, permitting lower-resolution ring and atmosphere studies to be pursued and providing the first views of Saturn's outermost satellite, Phoebe. Analysis of the anomaly continues, and there is reason to believe that the scan platform will remain operable for Voyager 2's Uranus encounter.

Although the trajectory at Saturn was dictated primarily by the desire to continue on to Uranus, the timing of the encounter was chosen to provide close approaches to Enceladus and Tethys and closer observations of Hyperion, Iapetus, Phoebe, and several of the recently discovered satellites than were afforded by Voyager 1. Voyager 2's path through the satellite system of Saturn is illustrated in Figs. 1 and 2.

Voyager 2 encounter activities commenced on 5 June 1981, with the spacecraft 77 million kilometers (47 million miles) from Saturn. Closest approach, at a distance of 100,800 km (62,600 miles) above Saturn's cloud tops, occurred at 0324 UTC (coordinated universal time) on 26 August 1981. The encounter period extended until 25 September 1981, although observations by the four scan platform instruments ceased with the completion of the Phoebe observations on 5 September 1981. The remaining investigations continued through the end of the encounter period.

The design of the Voyager 2 science sequences was particularly responsive to the findings of Voyager 1. All known satellites of Saturn were targeted for observation by Voyager 2, with special emphasis on satellites or surface areas not imaged by Voyager 1. The surprising ring detail seen by Voyager 1 led to a number of sequences for studying ring dynamics, especially in the vicinity of the F ring, the B ring spokes, and the eccentric rings. In light of its lack of visual detail due to its surface-obscuring atmospheric hazes, Titan observations were deemphasized, except for studies of the hazes themselves. Low-latitude, auroralike emissions discovered by Voyager 1 were studied in more detail with Voyager 2's ultraviolet spectrometer, and synoptic maps of the infrared emission of Saturn's atmosphere were moved closer to the planet to provide better latitude resolution. Imaging observations were designed for optimal measurement of zonal cloud velocities, extending those measurements to much higher latitudes than provided by Voyager 1. A number of unexpected details in Voyager 1 high time resolution plasma wave and planetary radio astronomy data led to a substantial increase in the amount of such data during the 24-hour period surrounding closest approach of Voyager 2, especially during and near the time of ring plane crossing (54 minutes after

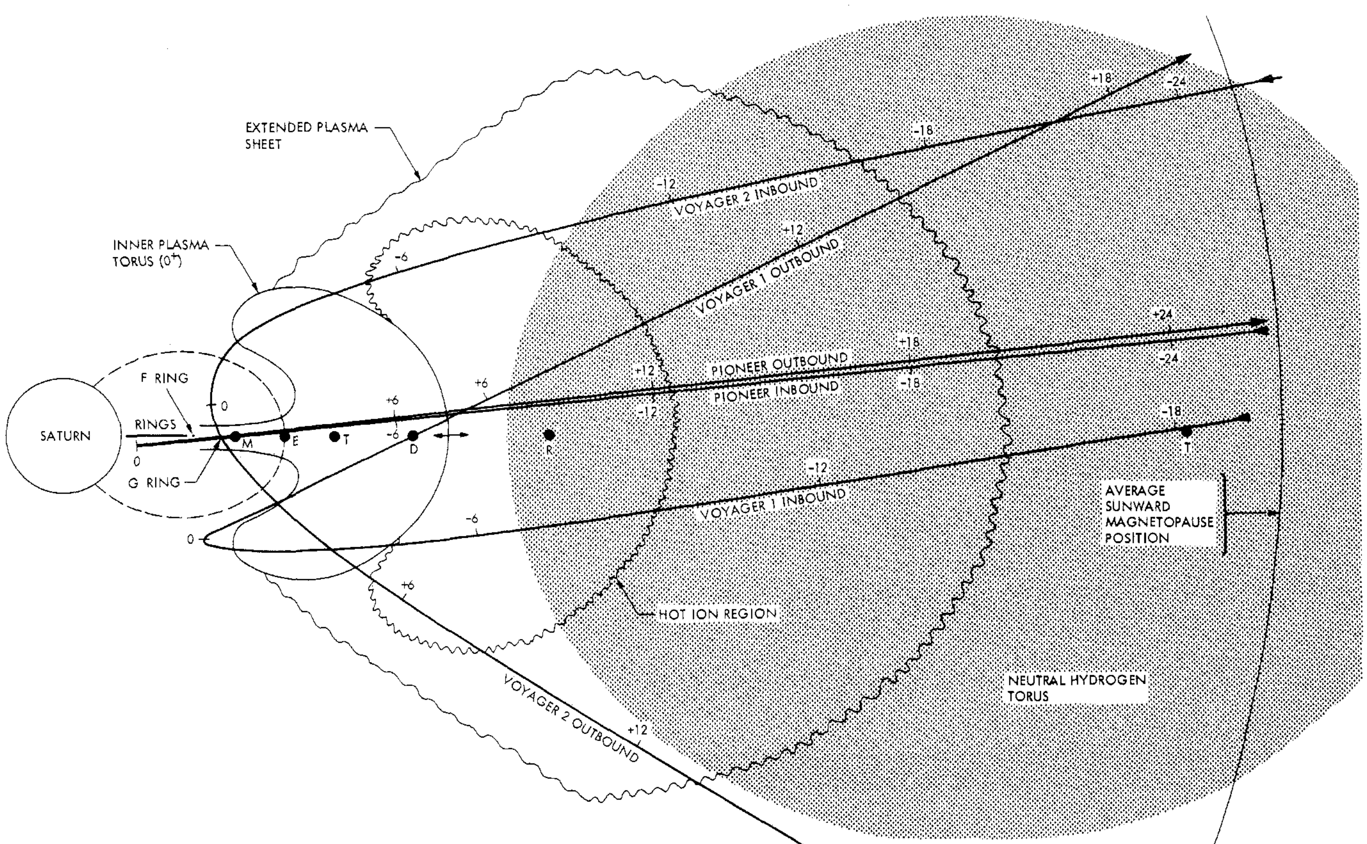

Fig. 3. Schematic cross section of Saturn's magnetosphere. Shown in meridional projection are the time-tagged (hours from Saturn closest approach) paths of Pioneer 11, Voyager 1, and Voyager 2. Ring plane (magnetic equator) crossings for Pioneer 11 occurred just outside (inbound) and inside (outbound) the G ring. Voyager 1 crossed the ring plane near the orbits of Titan (inbound) and Dione (outbound). Voyager 2's crossing occurred about 5000 km outside the center of the G ring. Shown schematically are cross sections of Enceladus' magnetic L shell, the inner plasma torus of ionized oxygen, the extended plasma sheet (including a hot ion region), the neutral hydrogen torus, and the average position of the sunward boundary of Saturn's magnetosphere.

closest approach to Saturn). Magnetospheric observation sequences were added to take advantage of the deeper penetration of the Saturn magnetic field by Voyager 2, especially near the Saturn equatorial plane, which very nearly coincides with the magnetic equator (and the plane of the rings). Figure 3 depicts in a meridional projection the paths of Pioneer 11 and the two Voyagers through the Saturn magnetosphere, showing the complementarity of the magnetospheric regions sampled by each of the three spacecraft.

Saturn's atmosphere. The Voyager 2 images of Saturn provided much new information on the dynamics of the atmosphere, both because the Voyager 1 experience permitted optimization of exposure times and filters and because the Voyager 2 vidicon was more sensitive. With the increase in detail, the Saturnian atmosphere appears to have a number of key similarities with that of Jupiter. A number of long-lived oval spots dynamically resembled the Jovian white ovals, which are anticyclonic wind systems. One such Saturnian oval was 7000 by 5000 km (4000 by 3000 miles) with 100 m sec^{-1} (200 mile per hour) circumferential winds. As on Jupiter, there are high-speed jet streams with directions alternating between eastward and westward with increasing latitude, except that the pattern occurs at higher latitudes on Saturn. There are also intermittent eruptions of convective clouds similar to the Jovian equatorial plumes. The largest longitudinal temperature variations occur at the same latitudes as these irregular convective clouds. Smaller convective clouds appear tilted in a manner which suggests that the jet streams are powered by small-scale eddies as in the Jovian atmosphere. The marked dominance of eastward jet streams on Saturn is an indication that the winds are not confined to the cloud layer but must extend at least 2000 km downward into the atmosphere. The winds may extend much deeper since the symmetry of the jet stream pattern in the northern and southern hemispheres is consistent with the concept that the wind pattern extends from north to south through the interior in the form of differentially rotating, coaxial cylinders. High-speed jet streams at high northern latitudes are also inferred from the temperature measurements.

Voyager 2's passage behind Saturn permitted the spacecraft radio beam to probe two more areas of the planet's atmosphere near 36.5°N and 31°S, complementing the near-polar and equatorial measurements made by Voyager 1. These measurements indicate minimum temperatures of about 82 K near the 70-mbar level, increasing to 143 ± 6 K at the deepest level probed (1.2 bars), consistent with data from Voyager 1. At the 100-mbar level, infrared measurements revealed that north polar temperatures were about 10 K colder than mid-latitude temperatures at the same pressure level, presumably a seasonal effect.

Another similarity to Jupiter is the presence of ultraviolet-absorbing material in the upper atmosphere at latitudes above ~ 65°. As on Jupiter, it is suggested that high-latitude auroral activity leads to the formation of complex hydrocarbon molecules, which are convected toward the equator. Direct observation of the ultraviolet emission from the aurora indicates that it occurs within 12° of the pole and is variable in intensity. The longitude and local time of maximum auroral activity is similar to that for the Saturnian kilometric radio emission, suggesting a direct connection. A similar ultraviolet emission from H_2 at lower latitudes appears to be unrelated to the precipitation of energetic particles that causes the aurora, since the low latitude emission depends on sunlight. The source of this emission is still a puzzle.

Rings. Voyager 2 returned significant information on the rings, both because it was possible to measure the amount of light from the star Delta Scorpii transmitted through the rings (the stellar occultation) and because it obtained much higher resolution images of the illuminated face of the rings. The stellar occultation measurements by the photopolarimeter provided a typical radial resolution of ≲ 300 m. It was found that even at this scale very few gaps exist in the rings. The edges of the rings at the gaps that do exist are so sharp, however, that the rings must be ≲ 200 m thick at those locations.

Since there are so few gaps, most of the radial structure in the B ring must be due to variations in the optical thickness of the rings resulting from density waves, gravitational instabilities, or dynamical instabilities. Density waves are excited by the gravitational effects of the Saturnian satellites and propagate outward from the resonant orbits where the ring particles orbit Saturn in synchronism with the satellite. For example, at the 2:1 resonant point with satellite 1980S1, there is a series of outward propagating density waves with characteristics which indicate that in that region of the B ring there is ~ 60 g of material per square centimeter of ring area and that the relative velocities of the ring particles are ≲ 1 mm sec^{-1}.

The outer edge of the B ring is elliptical with a difference of ≳ 140 km in the semimajor and semiminor axes, a somewhat larger difference than predicted by the 2:1 resonant interaction with Mimas. However, the axes of the ellipse rotate with the orbital motion of Mimas, as predicted. There are numerous radial variations with scales of 20 km in the outer B ring which are also noncircular, presumably the result of waves or instabilities. Radial features with scales of 500 km, however, appear to be circular.

In almost every case where clear gaps appear in the rings, eccentric ringlets are found. All seem to exhibit azimuthal brightness variations, due at times to variable radial extent of the rings and at other times to "kinks" or concentrations of ring particles or to nearly complete absence of ring material at various azimuthal positions. Two separate discontinuous ringlets were seen in the A ring gap near 2.21 Saturn radii (R_S) from the center of Saturn (1 R_S = 60,330 km = 37,490 miles). At high resolution, at least one of these ringlets is multiply stranded.

Although the presence of gaps and eccentric ringlets suggests that there are imbedded moonlets that are responsible, a systematic search for small satellites in the ring gap at the inner edge of the Cassini division yielded negative results. The nondetection sets an upper limit to the diameter of any unseen moonlets of 5 to 9 km (3 to 6 miles), depending on the assumed surface reflectivity. Although no systematic searches were conducted in the other ring gaps, the limited regions that were imaged revealed no moonlets.

The multistranded narrow F ring received considerable attention in replanning the Voyager 2 observations. At 15-km (9-mile) resolution, the F ring was seen to consist of one bright strand and four fainter ones, each ~ 70 to 100 km across, which, at least in that segment of the ring, did not appear to be braided or intertwined. The photopolarimeter stellar occultation showed that even the brightest strand was subdivided into numerous narrower strands about 3 km wide, possibly as a result of larger particles in the ring. Clumps of material in the F ring were observed over 15 orbits. The clumps are quasi-uniformly distributed about the ring every ~ 9000 km, a spacing that coincides with the relative motion of F ring particles and the shepherding satellites in one orbital period.

The "spokes" or clouds of micrometer-sized particles observed between 1.72 R_S and the outer edge of the B ring were also studied. Time-lapse sequences by Voyager 2 revealed that the spokes that are narrow and radial in alignment (hence presumably more recently formed) very nearly corotate with Saturn's magnetic field. Broader, less radial spokes appear to be remnants from earlier epochs (perhaps as much as several orbits earlier) and follow Keplerian orbits. In some cases, "new" spokes may be reprinted over preexisting ones. Spoke formation is not limited to regions near the planetary shadow, although spokes are more readily seen at the ring ansa near which ring particles have most recently exited the shadow. Spokes are also seen at high phase angles in reflected Saturn light on the unilluminated face of the rings, suggesting that their formation may not be dependent on photoelectrically induced charging effects.

Voyager 2 provided higher resolution color images of the entire ring system than were previously available. These reveal color differences within each of the major rings in addition to the differences between rings noted in Voyager 1 images. The color differences may be due in part to differences in optical depth between various parts of the rings, but may also indicate small compositional differences that have been preserved over geologic time.

The general dimensions of the main rings are given in Table 1, based on Voyager 1 and Voyager 2 imaging, radio science, and ultraviolet observations. More precise numbers will eventually be available from Voyager 1 radio science and Voyager 2 photopolarimeter measurements. However, some of these features may not have constant radial distances from Saturn.

Improved images of the D, G, and E rings were also obtained by Voyager 2, providing better measurements of their positions, optical depths, and radial extents.

Satellites. Voyager 2 imaged all of Saturn's known satellites, which now number 17. There is an indication from charged particle shadowing effects that additional material, possibly another small satellite, exists in approximately the same orbit as Mimas [see also (*6*)]. New masses for Iapetus and Tethys were derived from Voyager trajectory measurements, leading in addition to a revised estimate of Mimas' mass. The resulting density estimates and other characteristics of the satellites are summarized in Table 2. It now appears that, with the exception of Titan, there may be a tendency toward decreasing density for the regular satellites with increasing radial distance from Saturn, as is the case for the Galilean satellites of Jupiter.

There is also a tendency for the brighter satellites to be the most evolved, while the darker ones are more primitive and usually irregularly shaped. Thus the surfaces of the darker objects such as 1980S28 may be representative of the original mixture of rock and ice, while the brighter surfaces of evolved satellites such as Tethys and Enceladus may be the result of internal activity that melted the icy surfaces.

Phoebe is perhaps the most anomalous of the satellites. It orbits in a retrograde direction in a plane much nearer the ecliptic plane than Saturn's equatorial plane, leading to the suggestion that it is a captured asteroid. From Voyager 2 it is now known that Phoebe is roughly spherical with a 220-km diameter, spinning on its axis approximately once every 9 hours. Its surface is very dark (albedo = 0.06) and probably quite red, consistent with the properties of the class of asteroids believed to be very primitive and unmodified. If so, the images of Phoebe would be the first of such an asteroid.

Iapetus has long been known to have large albedo differences across its surface. Voyager 2 provided a view of this satellite that revealed a surface with the widest range of albedo values seen on any single body in the solar system: its dark material reflects only 5 percent of the sunlight, whereas the bright surface areas reflect 50 percent of the incident sunlight. The bulk of the dark material has a distribution that is precisely centered on the leading face of Iapetus in its orbital motion, supporting the conjecture that the dark material was swept up as it spiraled inward, presumably from Phoebe. The trailing face of Iapetus, however, has a number of craters with darkened floors, implying that the dark material originates in the interior of the satellite. It is possible that both processes occurred on Iapetus.

Hyperion appears to show no evidence for internal activity. Its irregular shape and the remaining evidence of heavy bombardment by meteoritic and asteroidal material indicate that it may have the oldest surface in the Saturn system. Its rather dark surface may also have been contaminated by the deposition of darker material.

Voyager 2 images of Tethys revealed an enormous impact structure, nearly one-third the diameter of Tethys itself and larger than the satellite Mimas. It appears to have formed when Tethys was relatively warm, since following the impact the satellite surface recovered almost to its original shape. Tethys' current surface temperature, however, is only 86 ± 1 K. A gigantic fracture spans three-quarters of Tethys' circumference. If Tethys was fluid in its past, and its crust hardened before its interior, the freezing and consequent expansion of the interior would cause a surface spreading of approximately the dimensions seen for this feature, called Ithaca Chasma. However, such spreading would not be expected to be concentrated in a single, circumferential fracture.

By far the most active satellite surface yet seen in the Saturn system is that of Enceladus. At least five types of surface units have been identified, with the youngest, least cratered areas being less than a few hundred million years old. Indeed, it seems likely that the surface of Enceladus is still undergoing change. Other evidence for tectonic activity is provided by orthogonal patterns of rectilinear faults and ridged plains that have curvilinear valleys similar to those observed on Ganymede. It seems unlikely that radioactive nuclides could provide sufficient heating in such a small body to cause the changes noted. A more likely source of heating is tidal interaction with Dione, although current theoretical estimates seem to be too low, given the observed eccentricity of Enceladus' orbit. Because Enceladus is so reflective, its surface temperature is only 72 K.

Titan, which is a planet-sized satellite, was studied intensively by Voyager 1 and more remotely by Voyager 2, which concentrated on studies of Titan's photochemical haze layers. In the images, the main opaque haze layer peak occurs 183 ± 30 km above Titan's surface in the north and 50 km higher in the south, thought to be a seasonal difference. The absence of any measurable change in the haze albedo between Voyager 1 and Voyager 2 indicates a large seasonal lag in atmospheric changes, which therefore must be associated with the more massive deeper atmosphere. Although the mean radius of the particles in the haze layer is ~ 0.5 μm, polarization measurements require either that there be a range of particle sizes down to ~ 0.05 μm, or (perhaps more likely) that the particles be nonspherical. In the much thinner upper haze layer, which is 314 ± 30 km above Titan's surface, the mean radius of the particles is 0.3 μm.

Titan's atmosphere is also the source of a torus of neutral hydrogen atoms which surrounds Saturn between 8 and 25 R_S. The torus extends 7 to 8 R_S above and below the equatorial plane and has a mean density of 20 H atoms per cubic centimeter with a lifetime against ionization of ~ 10^8 seconds, requiring a supply rate of 10^{27} H atoms per second from Titan.

Magnetosphere. The Voyager 2 flyby produced further puzzles about Saturn's internal magnetic field. The discovery of recurring radio emission by Voyager 1 suggested that the Saturnian magnetic field possessed a large-scale longitudinal asymmetry that resulted in radio emission every rotation of the planet. The Voyager 2 flyby, even though closer than that of Voyager 1 and at higher latitudes than Pioneer 11, found no evidence for any significant asymmetry of the magnetic field other than the ~ 1° tilt with respect to Saturn's rotation axis previously reported from Voyager 1 data. Also puzzling were observations of absorption of trapped particles by Mimas, Enceladus, and Tethys. Such absorption shadows, which extend to higher latitudes along the magnetic field lines threading the satellites, were not observed at the distances predicted by the magnetic field models.

The size of Saturn's magnetosphere is determined by external pressure from the solar wind. The pressure was high and the magnetosphere extended sunward only ~ 19 R_S when Voyager 2 first entered it. Several hours later, however, the external pressure apparently dropped, followed by inflation of the magnetosphere over an ~ 6-hour period. Evidently the magnetosphere remained inflated for at least 3 days, since it was 70 percent larger at the time Voyager crossed the magnetospheric boundary outbound. During this time the Saturnian kilometric radio emission dropped below detectability, perhaps due to the reduction in the external pressure on the magnetosphere.

Since Voyager 2 had earlier detected the Jovian magnetotail extending at least three-fifths of the distance from Jupiter to Saturn, it is possible that the reduced pressure and absence of radio emission resulted from immersion of Saturn in the extended Jovian magnetotail or the asso-

Table 1. Saturn ring data.*

Feature	Distance (km)	Distance (R_S)	Comments
Equatorial radius	60,330	1.000	Near the 100-mbar level in Saturn's atmosphere
D ring inner edge	67,000	1.11	Onset of ringlet structure in images
C ring inner edge	74,400	1.233	Onset in radio data of signature of individual ringlets; C ring features seen in images down to ~ 73.200 km
B ring inner edge	91,900	1.524	Sharp increase in optical depth (radio plus ultraviolet)
B ring outer edge	117,400	1.946	Outer edge variable by at least 140 km; spokes between 1.72 R_S and outer edge of B ring = inner edge of Cassini division
A ring inner edge	121,900	2.021	Sharp increase in optical depth (radio plus ultraviolet); outer edge of Cassini division ambiguous in imaging data
A ring gap center	133,400	2.212	Encke or Keeler gap ~ 320 km wide
A ring outer edge	136,600	2.265	Sharp decrease in optical depth (radio plus ultraviolet)
F ring center	140,300	2.326	Eccentric ring; multiple strands; edges not well defined (radio plus ultraviolet)
G ring center	170,000	2.8	Optical depth ~ 10^{-4} to 10^{-5}
E ring inner edge	180,000†	3†	Not well defined; maximum brightness near the orbit of Enceladus
E ring outer edge	480,000†	8†	Not well defined; maximum optical depth ~ 10^{-6} to 10^{-7}

*Data presented here are preliminary. Some discrepancies exist between data sets. The R_S distances given to one decimal place are accurate to within about 0.05 R_S; two-decimal precision implies an accuracy of about 0.02 R_S; precision to three decimals implies an accuracy of about 0.003 R_S; these numbers should eventually be improved to an accuracy of about 10 km = 0.0002 R_S. †E ring dimensions are from Baum *et al.* (9). Voyager imaging shows little evidence of the E ring inside 3.5 R_S or outside 5 R_S, presumably because of the low light levels involved.

Table 2. Saturn satellite data.

Name	Diameter (km)	Distance* (km)	Distance* (R_S)	Period* (hours)	Best imaging† resolution (km/lp)	Density (g/cm³)	Albedo
1980S28	40 × 20	137,670	2.282	14.446	13(1)		0.4
1980S27	140 × 100 × 80	139,350	2.310	14.712	7(2)		0.6
1980S26	110 × 90 × 70	141,700	2.349	15.085	8(2)		0.6
1980S3	140 × 120 × 100	151,422	2.510	16.664	3(1)		0.4
1980S1	220 × 200 × 160	151,472	2.511	16.672	6(1)		0.4
Mimas	392 ± 6	185,540	3.075	22.618	2(1)	1.44 ± 0.18	0.7
Mimas companion	?	~ 186,000	~ 3.1	?	−(2)		
Enceladus	500 ± 20	238,040	3.946	32.885	2(2)	1.16 ± 0.55	1.0
Tethys	1,060 ± 20	294,670	4.884	45.307	2(2)	1.21 ± 0.16	0.8
1980S13	34 × 28 × 26	294,670	4.884	45.307	12(2)		0.6
1980S25	34 × 22 × 22	294,670	4.884	45.307	5(2)		0.8
Dione	1,120 ± 10	377,420	6.256	65.686	3(1)	1.43 ± 0.06	0.5
1980S6	36 × 32 × 30	378,060	6.267	65.738	6(2)		0.5
Rhea	1,530 ± 10	527,100	8.737	108.42	1(1)	1.33 ± 0.09	0.6
Titan	5,150 ± 4	1,221,860	20.253	382.69	1(1)	1.88 ± 0.01	0.2
Hyperion	410 × 260 × 220	1,481,000	24.55	510.64	9(2)		0:3
Iapetus	1,460 ± 20	3,560,800	59.022	1,903.94	17(2)	1.16 ± 0.09	0.5, 0.05
Phoebe	220 ± 20	12,954,000	214.7	13,210.8	38(2)		0.06

*Note that most of the satellite orbit parameters published in the Voyager 1 Saturn issue (3) were in error by small amounts. Periods and distances given here for the five inner satellites and the Dione companion are from Synnott *et al.* (10); these periods and distances are for the time of Voyager 1 closest approach and are likely variable. 1980S6, for example, is likely to have the same orbital elements as Dione when averaged over a long time interval. Periods for the named satellites are from Newburn and Gulkis (7); distances for these satellites utilize updated values for Saturn's gravity harmonics (8). Periods and distances for Tethys' companions are assumed identical to those of Tethys. †Geometric resolution given in kilometers per imaging line pair; the number in parentheses indicates whether the best imaging was obtained by Voyager 1 or Voyager 2.

ciated wake. Before the encounter, when Jupiter and Saturn were nearly radially aligned from the sun and Saturn was therefore most likely to be affected by a Jovian magnetotail, there were a number of other periods during which the radio emission was undetectable. Although the observations are consistent with effects due to the Jovian magnetotail, there is currently no direct evidence that this was the situation.

Voyager 2 also acquired new information on the plasma and energetic particles in the magnetosphere. Combining these new results with the Voyager 1 and Pioneer 11 results, it is possible to identify several distinct regions, as shown in Fig. 3. Inside 6 or 7 R_S there is an inner torus of H^+ and O^+ ions, probably originating from the sputtering of water ice from the surfaces of Dione and Tethys and extending several R_S above and below the magnetic equator. Inside Enceladus' orbit, however, the torus is concentrated near the magnetic equator. At the outer edge of this inner torus, there are energetic ions with 30- to 50-keV temperatures. Strong plasma wave emissions also appear to be associated with the inner torus. Beyond the inner torus there is a very thick sheet of plasma extending out to $\sim 17 R_S$. The source of material for the outer plasma sheet is likely the ionosphere of Saturn, the atmosphere of Titan, and the neutral hydrogen torus that surrounds Saturn between ~ 8 and $\sim 25 R_S$. The observation of energetic H_2^+ and H_3^+ molecules strongly indicates an ionospheric source for some of the material.

Observations by Voyager 2 of Saturnian kilometric radio emission also provide evidence for a south polar source of emission. It appears to be much weaker than the radiation from the north polar region. Evidence for a frequency-dependent modulation of the radio emission by Dione was also obtained. Saturn electrostatic discharges were observed by Voyager 2 but at a rate approximately 10 percent that of Voyager 1 and with significantly different polarization characteristics, suggesting a dynamic source.

Summary. The Voyager 2 flyby completes the currently planned spacecraft observations of Saturn. The data acquired by the Pioneer and Voyager spacecraft have already revolutionized our knowledge and understanding of the Saturnian system. As the detailed analysis progresses over the next few years, our understanding will continue to grow and thoughtful consideration can be given to the nature of a future mission to Saturn.

In the meantime, the Pioneer and Voyager spacecraft will extend the exploration of the interplanetary medium to ever-increasing distances from the sun. In 1990 Voyager 1 will be 40 AU from the sun, perhaps approaching the boundary of the heliosphere—the bubble that the solar wind is blowing in the surrounding interstellar medium. By that time, Voyager may already have detected the low-energy cosmic-ray particles from nearby sources which are excluded from the solar system by the outward flowing solar wind.

During this same time period, Voyager 2 will be encountering two more planets in the outer solar system. Voyager 2 is scheduled to begin observing Uranus in late 1985, with closest approach on 24 January 1986, and continuing on to an encounter with Neptune and its satellite Triton on 24 August 1989. Given that the spacecraft, which were designed for the 4-year mission to Saturn, will continue to operate well into the future, there will be the opportunity for still more major discoveries about the solar system.

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11. We wish to pay special tribute to the dedicated members of the Voyager Project team, without whom the scientific data reported in this issue could not have been collected. The Voyager Program is one of the programs of the Planetary Division of NASA's Office of Space Science. The Voyager Project is managed by the Jet Propulsion Laboratory of the California Institute of Technology under NASA contract NAS 7-100.

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A New Look at the Saturn System: The Voyager 2 Images

Abstract. *Voyager 2 photography has complemented that of Voyager 1 in revealing many additional characteristics of Saturn and its satellites and rings. Saturn's atmosphere contains persistent oval cloud features reminiscent of features on Jupiter. Smaller irregular features track out a pattern of zonal winds that is symmetric about Saturn's equator and appears to extend to great depth. Winds are predominantly eastward and reach 500 meters per second at the equator. Titan has several haze layers with significantly varying optical properties and a northern polar "collar" that is dark at short wavelengths. Several satellites have been photographed at substantially improved resolution. Enceladus' surface ranges from old, densely cratered terrain to relatively young, uncratered plains crossed by grooves and faults. Tethys has a crater 400 kilometers in diameter whose floor has domed to match Tethys' surface curvature and a deep trench that extends at least 270° around Tethys' circumference. Hyperion is cratered and irregular in shape. Iapetus' bright, trailing hemisphere includes several dark-floored craters, and Phoebe has a very low albedo and rotates in the direction opposite to that of its orbital revolution with a period of 9 hours. Within Saturn's rings, the "birth" of a spoke has been observed, and surprising azimuthal and time variability is found in the ringlet structure of the outer B ring. These observations lead to speculations about Saturn's internal structure and about the collisional and thermal history of the rings and satellites.*

The Voyager 1 encounter with the Saturn system in November 1980 extended the U.S. program of planetary exploration to nearly 1½ billion kilometers from the sun, adding more than a dozen new worlds as well as Saturn's extraordinary ring system to our catalog of solar system discovery. About 9 months later Voyager 2 followed on a different trajectory through the Saturn system, en route to more distant rendezvous with Uranus (in 1986) and Neptune (in 1989).

The Voyager 2 trajectory, although constrained by the requirements of a transfer to Uranus, was able to provide a