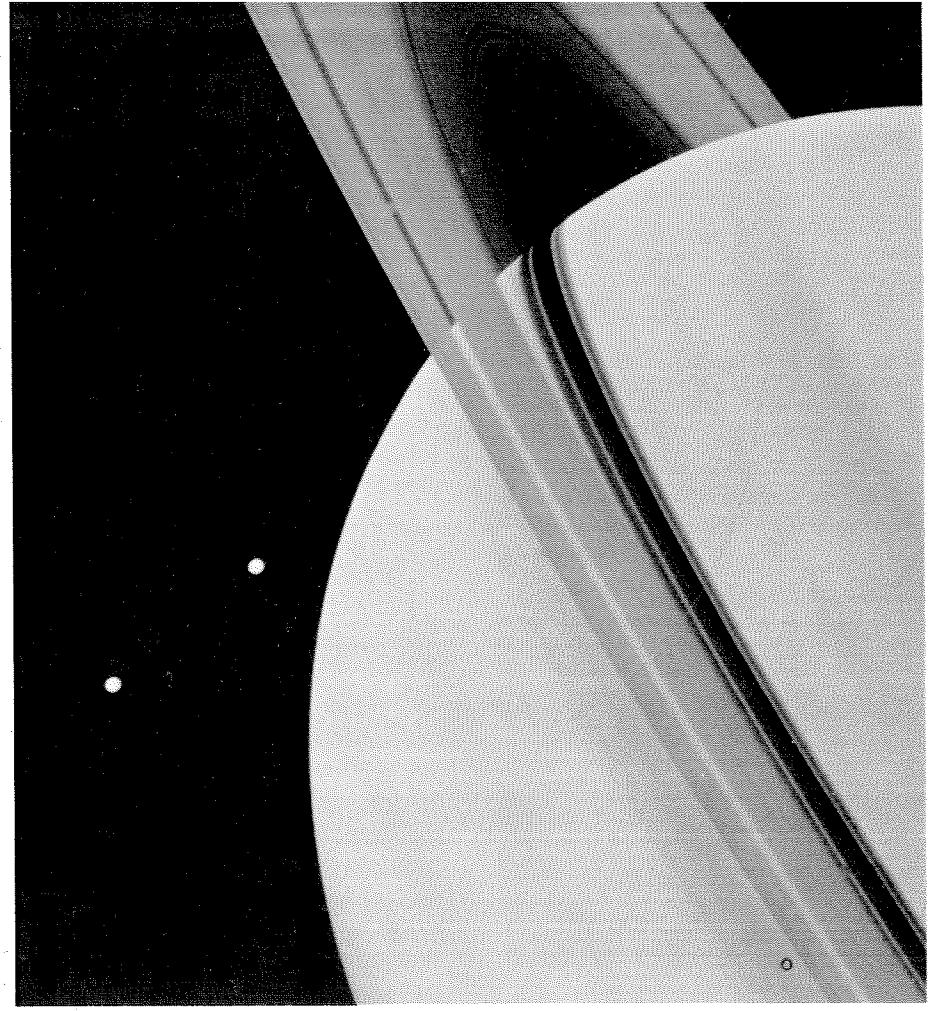


# Voyager 1 at Saturn

## An Encounter with a Multi-ringed Giant

by EDWARD C. STONE

The Voyager project, a national enterprise involving several thousand individuals who built the spacecraft, several hundred at Caltech's Jet Propulsion Laboratory who fly it, and approximately a hundred scientists who are analyzing the data, began, in a sense, with one man and his telescope. In 1610 Galileo turned that telescope toward Saturn and observed some odd appendages, somewhat like cup handles. It wasn't until about 45 years later that Huygens with an improved telescope deduced that Saturn had a ring. He saw it as a single ring, a solid structure somehow suspended around Saturn. It was another 21 years before Cassini found that there wasn't *a* ring, but two rings around Saturn (the division between them is called the Cassini Division). Since that time, three more rings were reported by Earth-based observers, and Maxwell proved that the rings could not be solid structures but must consist of a large number of small bodies in orbit about Saturn.

Only a short time ago, in 1979, the Pioneer 11 spacecraft visited Saturn and discovered the F-ring, making a total of six known rings at that time. That number changed dramatically with the Voyager spacecraft, which visited Saturn in November 1980 and sent back many surprises in its close-up views not only of Saturn's rings and its satellites but of the planet itself.

Saturn is one of the giant planets in the outer solar system. Deep inside Saturn is a rocky core about the size of the Earth and approximately five times as massive, but the bulk of Saturn is hydrogen, the lightest element. With so much hydrogen, the density of the planet is only seven-tenths that of water, so that if there were an ocean large enough, Saturn would float with three-tenths of its volume above the surface — a remarkably low-density giant planet.

Saturn's atmospheric dynamics, or weather, was one area that Voyager was scheduled to study, as it had already done with Jupiter's atmosphere. Jupiter has very pronounced alternating zones of white clouds separated by dark bands or belts. The white clouds form when the atmospheric gases, which become colder as they rise from the warmer interior, reach the altitude at which it is cold enough for ammonia to liquefy or freeze. Voyager's view of Saturn showed a much more subdued cloud structure but still with evidence for belts and zones. Since Saturn is twice as far from the sun as Jupiter, it is colder, and the altitude at which the ammonia freezes is deeper in Saturn's atmosphere. The clouds are thus obscured by considerable haze in the overlying atmosphere with the result like that on a smoggy day in Los Angeles — a great deal of contrast and color is lost. But it is still possible to improve our basic understanding of weather processes by a comparative study of the wind systems of Saturn and Jupiter.

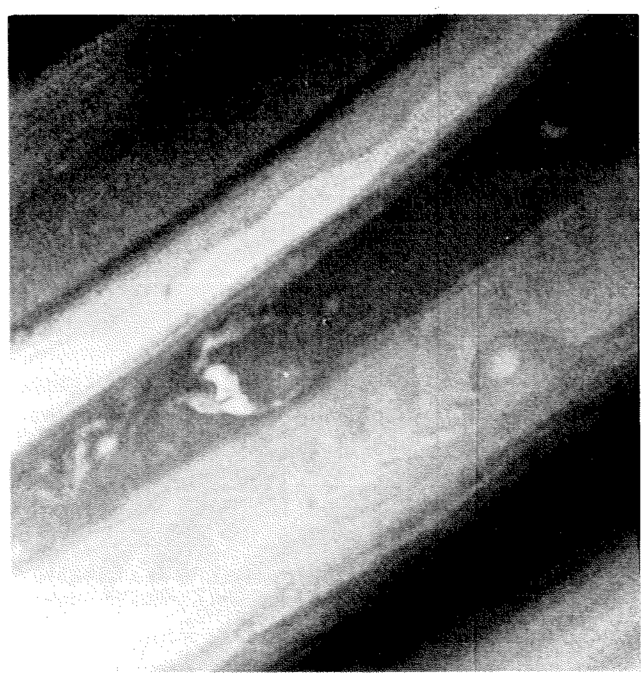
Before Voyager, Caltech's Andrew Ingersoll, professor of planetary science, developed a model to explain the formation of these belts and zones. He postulated an upwelling of gas from the interior of the planet, and the consequent formation of the ammonia clouds results in the formation of an elevated ridge in the atmosphere which would like to flow directly north or south into the adjacent lower belt regions. Because of the rotation of the planet, however, wind is deflected much as here on Earth, resulting in alternating eastward and westward jet streams on opposite edges of each zone, as suggested by ground-based observations.

So even before the encounter with Jupiter, we expected to find alternating eastward and westward jets associated with the white cloud regions. Voyager 1 found that in the equatorial region there is a 200 mph eastward wind extending from about 10 degrees north latitude to about 10 degrees south. With increasing latitude, there are alternating westward and eastward jets that are indeed associated with the white zone cloud structure.

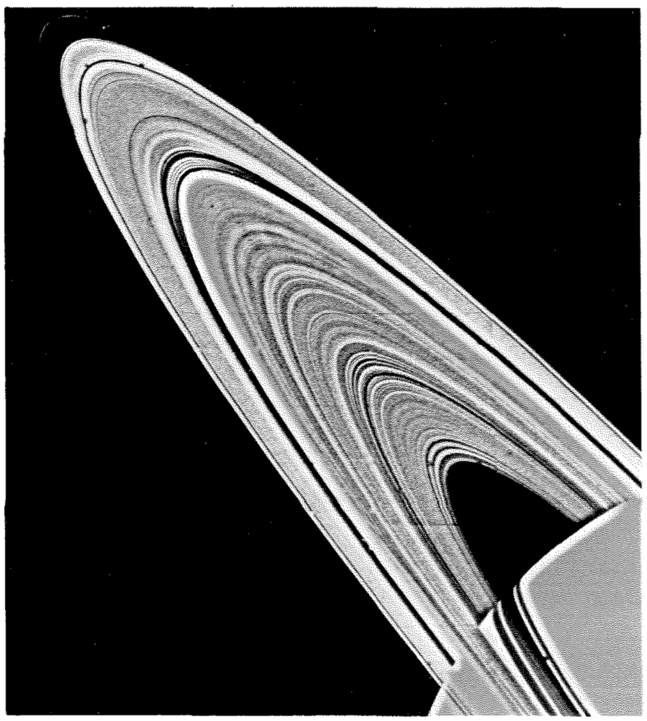
Because of the apparent lack of contrast on Saturn these zone patterns weren't as obvious. Fortunately, Voyager's images can be enhanced by making regions that are somewhat red, still redder, and regions farther north, which are a bit blue, bluer. With such techniques, distinct features emerge from the rather bland images — discrete white clouds, which are likely the result of conductive upwellings, and wavy, high-speed jet streams. There is even a small red spot which is about the size of the Earth.

Saturn's clouds can be located in several successive enhanced images, their displacement and velocity measured, and a wind pattern derived. These patterns appear very different from those on Jupiter. Not only does Saturn have an eastward wind speed at the equator of almost 1000 miles per hour, about half the speed of sound, but the eastward winds occur from about 40 degrees south to 40 degrees north. It is only above this latitude that the pattern of alternating westward and eastward jets observed at lower latitudes on Jupiter begins to appear on Saturn. In a comparison of these winds with the cloud patterns on Saturn, there is almost no correlation at all. The winds are apparently independent of the formation of the belts and zones, suggesting that the correlation found on Jupiter was not a fundamental one and that the pattern of jet streams is the result of processes other than cloud formation.

The apparent differences in the weather systems, which are related to the dissimilarities between the planets themselves, provide clues to the origin of the jet streams. Jupiter and Saturn are different in a several key ways; one of these is their interior structure. They each have a rocky core about 4000 miles in radius, very similar to the size of the Earth and not unlike each other. Jupiter's central temperature is about 43,000 degrees Fahrenheit; it's somewhat colder inside Saturn. However, the bulk of both planets is a deep envelope consisting mostly of hydrogen. In the outer regions of both planets, the hydrogen is of the common molecular form ($H_2$), but at higher pressures deeper inside, hydrogen becomes a metal — not a solid, but a metal in the sense that it conducts electricity. Although Jupiter and Saturn both have an inner core of electrically conductive hydrogen surrounded by molecular hydrogen, the metallic core is much larger on Jupiter than it is on Saturn. Ingersoll has suggested that the observed jet streams are the result of large-scale motions in the deep layer of molecular hydrogen and that the size of these motions may be affected by the size of the metallic hydrogen



Saturn's atmospheric structure, while less pronounced than Jupiter's, shows alternating belts and zones and discrete smaller-scale features within the bands. There seems to be, however, no correlation between these zones and Saturn's wind patterns.



This computer-enhanced mosaic of Saturn's rings shows their extraordinary complexity. Literally hundreds of individual ringlets make up the B-ring, and even the Cassini Division is filled with rings. The F-ring is barely visible to the left outside the A-ring.

core. Whether or not such a model can explain both the Jupiter and Saturn wind patterns is a quantitative question that has not yet been answered.

Another possible explanation is that the jet streams are confined to a relatively thin surface layer. In this model, the upwelling of the deeper atmosphere, which is caused by the high temperatures at the planets' centers, results in localized upward bumping or punching of the bottom of the thin layer in which the jet streams occur. Each such upward bump generates a small whirling eddy in the thin layer, which eventually combines with countless others to generate the very strong wind systems. In this case, it would have to be shown that the production and distribution of these eddies is significantly different on Saturn than on Jupiter. Again, this is a quantitative question that has not been addressed.

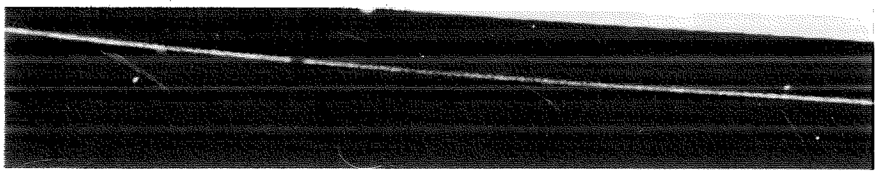
Voyager also delivered a number of surprises and raised many new questions about Saturn's rings. From Earth we can see the A-ring and the B-ring with the Cassini Division between them. Among Voyager's surprises was that the Cassini Division was not a gap at all but was filled with five rings, each about 300 miles wide. At still higher resolution those rings were found to be further subdivided into still more rings, resulting in several dozen individual rings altogether. The many particles comprising the rings are all in circular orbits around Saturn — except for the particles in a narrow ring in the Cassini Division and in another in the C-ring which are in eccentric orbits.

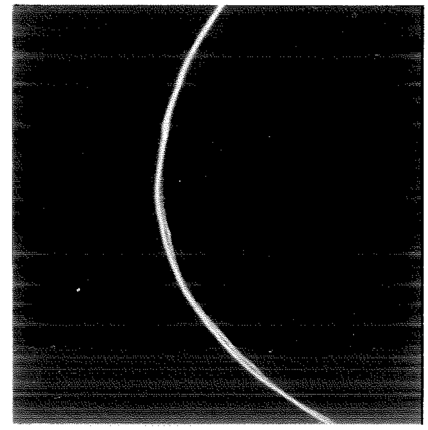
The next surprise was the B-ring, which from Earth appears as a very bright, uniform region. Voyager's enhanced images show that the B-ring is anything but uniform. It contains hundreds of individual ringlets, separated by narrow gaps through which the planet can be seen quite clearly, except in some regions where the rings are too thick or the gaps too narrow. From Earth, the B-ring appears uniform because of the unfavorable viewing geometry and great distance, although there are a few sketches by ground observers which indicated structure in the B-ring.

There were also a number of surprises associated with the very narrow F-ring, which Pioneer 11 discovered just 2800 miles outside the A-ring. Voyager found three new satellites, one just outside the A-ring and one on each side of the F-ring. Those satellites are probably why the F-ring and the edge of the A-ring are so sharply defined. Peter Goldreich, Lee A. DuBridge Professor of Astrophysics and Planetary Physics here at Caltech, and Scott Tremaine, formerly Richard Chace Tolman Research Fellow in Physics at Caltech and now associate professor of physics at MIT, published a theory some years ago to explain the rings around Uranus, which were discovered in 1977. These are very narrow rings, much like Saturn's F-ring. Their theory postulated the existence of a pair of satellites, one just inside and another just outside each ring. Because the satellites are in orbit around the planet, the closer object has to move more quickly and the one farther out more slowly. That means that the ring material is overtaking the outer satellite and, as a result, it gives the satellite a small push, increasing its energy. The ring material thus loses energy and falls in toward the planet, while the outer satellite moves outward. The inner satellite, on the other hand, is moving more rapidly than the ring material, so it's doing just the opposite — giving up energy to the ring material and pushing it outward. Thus, between the two satellites, the ring material is constantly shepherded back into place.

When this theory was proposed for the nine rings of Uranus, some felt that it was too complicated because in order to explain nine rings it was necessary to postulate the existence of 18 small satellites. Now that two such satellites have been discovered on either side of the F-ring, the theory would seem to be applicable at least in this case. In fact, the theory may also explain the multiple ringlets in the B-ring which may result from literally hundreds of tiny satellites in orbit around Saturn, shepherding the smaller ring particles into narrow rings. Unfortunately these small satellites, which may be only 1 mile in diameter, have not yet been found, since not a very large fraction of the ring was imaged at the high resolution required to find such small objects. But the fact that Voyager found the two shepherding satellites for the F-ring is certainly very suggestive that this simple, or perhaps not so simple, physical picture may also explain the structure in the B-ring.

Another interesting phenomenon that this theory might explain is the so-called "braid" in the F-ring. Rather than





Voyager discovered on either side of the F-ring two small satellites, whose presence had been previously postulated as being responsible for holding the ring material in narrow orbits. They may also deflect the ring material slightly, causing the "braid" (right) where there appear to be three separate ten-mile-wide strands.

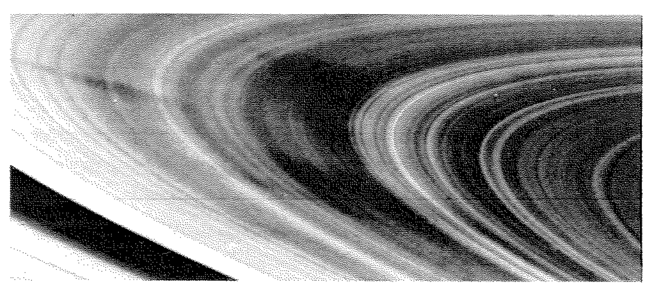
keeping the material in the F-ring nicely shepherded in perfectly circular orbits, the satellites may tend to deflect it slightly, resulting in a small ripple in the otherwise circular orbit. Rippling is exactly what the F-ring seems to do. In one place in the F-ring there are three separate strands, each about 10 miles wide. Two of the strands seem to intersect each other, forming a braided appearance.

The visible material of the F-ring is known to be very fine, a few ten-thousandths of an inch in diameter, because it scatters sunlight forward very efficiently. Clumps or knots in the braids are possible sources of the fine material, which is most likely charged with static electricity due to action of sunlight and the Saturnian radiation belts. In this case the dust will also be interacting with Saturn's magnetic field, which is rotating with a period of 10 hours and 39 minutes. To what extent this interaction contributes to the braiding of the F-ring is a detailed quantitative question which has not yet been answered. But despite some of the press reports last November, there is nothing about the rings that violates physical laws. It is rather a question of understanding which physical laws are responsible for the observed effects.

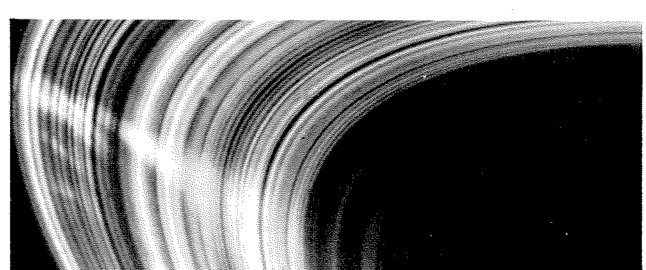
Still another surprise in the rings was the mottled dark regions in the B-ring, which were immediately described as "spokes" because of their radial appearance and because they seem to rotate with the B-ring. Although the nature of the spokes could not be discerned when first observed far from Saturn, from close-up approach images it was clear that the spokes were regions where the ring material appeared darker but not thinner or full of holes. However, the appearance of the spokes changed dramatically when viewed from behind Saturn. Since the sun and the spacecraft were then in opposite directions from the rings, the images were formed of forward-scattered sunlight and the spokes appeared bright rather than dark. Since scattering of sunlight preferentially in the forward direction is characteristic of very fine material, the spokes must be clouds of small particles — probably not rock dust but very fine ice particles a few ten-thousandths of an inch in diameter.

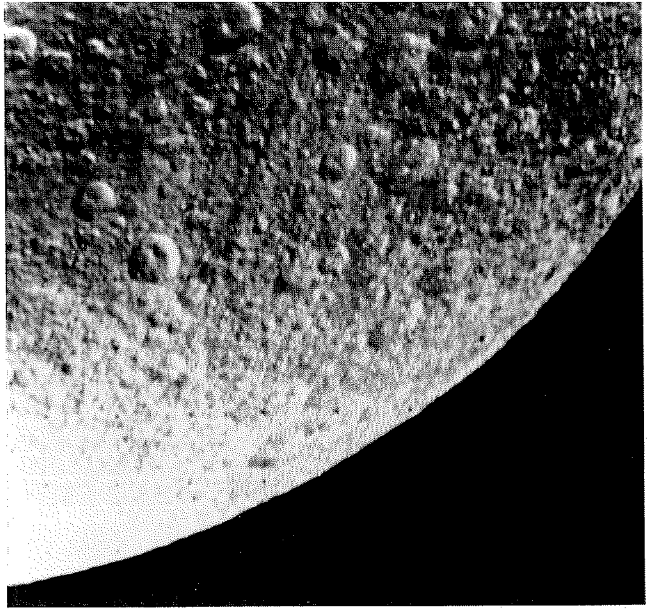
The mechanism that generates the irregularly shaped spokes isn't fully understood. They're not permanent; individual spokes appear — perhaps as the result of levitation of the small particles above the ring plane — and disappear in a matter of hours. New spokes seem to appear as the ring material comes out of the shadows behind Saturn suggesting that electrostatic charging may be involved. When objects are in sunlight, electrons are released from their surfaces by a photoelectric effect. In the dark the process ceases, perhaps resulting in a change in the electrical characteristics of the fine ring material (in a manner that is not yet well understood) that causes these clouds to form. Then they dissipate as they rotate around Saturn because the end of the spoke nearest the planet rotates more rapidly.

One other indication that electrical activity may be important in the rings comes from the two radio receivers which detected static electrical discharges of increasing intensity as the spacecraft approached the rings. The electrical discharges aren't from the planet because the lowest frequencies would have been trapped below Saturn's ionosphere and would not have been detected by Voyager. This suggests that the static discharges are coming from the rings and may be related to the electrical charging and discharging of the icy material that forms the rings.

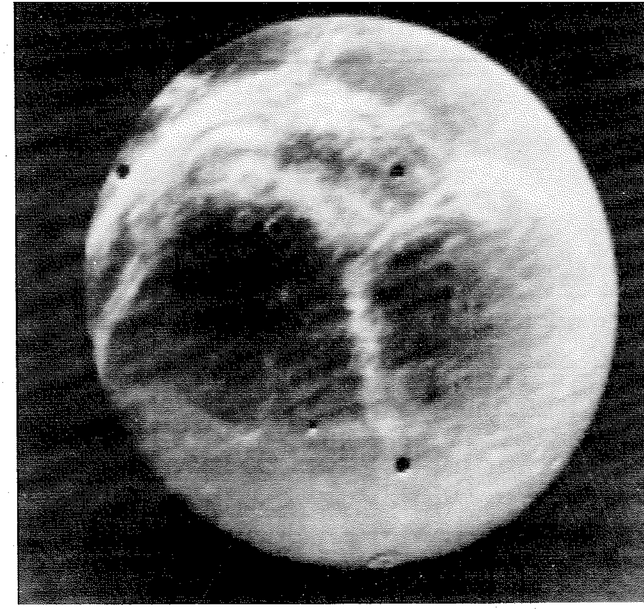


The rotating spokes of the B-ring appear dark in backscattered light (above) and bright in forward-scattered light (below) viewed from behind Saturn, indicating that the spokes are clouds of very small particles a few ten-thousandths of an inch in diameter.





Saturn's satellite Rhea is heavily cratered like the Earth's moon. The larger craters seen here in Rhea's ancient surface are about 45 miles across; the peaks in the centers are formed by the rebound of the surface after impact.



Dione's surface is marked by bright, wispy regions, which may be frost evolving out of extensive fracture systems. Rhea also exhibits these white patterns, indicating that there has been some sort of geologic activity since the two satellites formed.

Additional information on the rings was obtained when the spacecraft was behind the rings, as viewed from Earth. The attenuation of the radio beam transmitted from the spacecraft provided a measure of the amount of material in each of the rings and the size of the larger particles. The radio transmission indicated an effective size of 6 feet in diameter for the larger particles in the C-ring, 24 feet in the Cassini Division, and 30 feet in the A-ring. Since many, if not most, of the particles are somewhat smaller, further analysis is required in order to determine the range of sizes of the ring particles. What they are made of is still unknown, although ground-based studies indicate that they are at least covered with ice.

Voyager also sent back some fascinating views of Saturn's satellites. Saturn has five icy inner satellites which are a new size class; from the outside in they are Rhea, Dione, Tethys, Enceladus, and Mimas. Much farther from Saturn is the giant satellite Titan, about the size of the planet Mercury and the Galilean satellites Ganymede and Callisto. Saturn's icy inner satellites are much smaller, although not as small as typical asteroids. This is an interesting size class because some of the satellites are small enough that they might contain very little radioactive material and therefore may never have been hot enough to melt the ice. Thus, they may never have differentiated, that is, they might not have rocky cores because the ice and rock may not have separated.

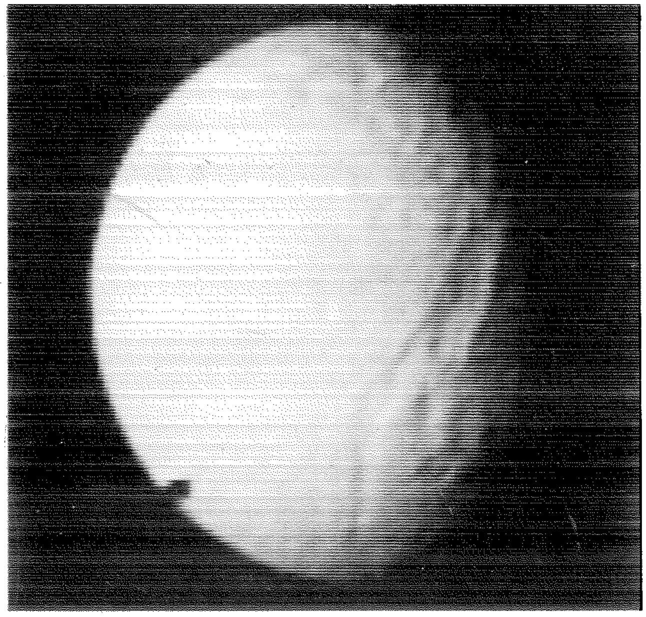
Rhea has a diameter of about 950 miles, which is large enough that melting of the ice could have occurred early in its formation, allowing the rock to sink to the center before the water refroze. The resulting icy surface was expected to be a uniform, heavily cratered old surface.

Rhea appears not to be quite as expected. From a distance, Voyager observed long wispy white regions — not a uniform surface at all. As the spacecraft came closer it was obvious that Rhea is indeed heavily cratered, with craters on top of craters, indicating a very old surface that formed when Rhea itself initially formed. In some regions, however, there is an absence of larger craters suggesting that those regions were resurfaced, possibly by flooding, shortly after the formation of the largest craters. Apparently Rhea did not form and then quickly freeze into a geologically dead object, but did manage to maintain some activity long enough to have erased some record of its early history.

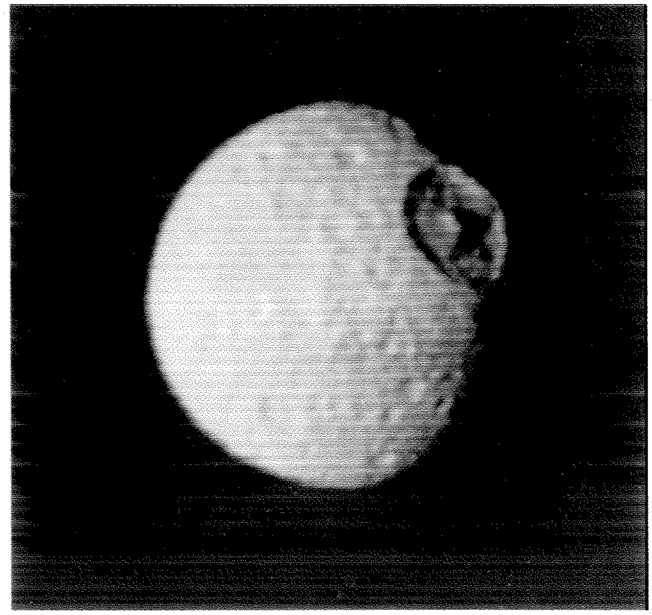
Rhea's craters are characterized by central peaks formed by the rebound where meteor impact punched the icy surface and depressed it. Because the temperature and the gravity are so low, the peaks have remained in the basic form that can be seen today. The craters are not perfectly circular. This suggests that the shock wave that traveled out forming the basin traveled in an inhomogeneous medium — probably large blocky regions of ice. The characteristic irregularity of these features is undoubtedly telling us something about the somewhat deeper surface material properties on Rhea.

Somewhat closer to Saturn, Dione and its twin, Tethys, are small enough — about 700 miles in diameter — that they might not have melted and might have rock and ice still mixed in whatever state they accumulated. If the rock had accumulated first, it would still be in the center, but if the ice and rock were mixed together as they accumulated, they would have remained that way. Dione's surface is not uniform but, like Rhea's, is marked with large, white wispy regions. There is also a region that was flooded late enough that not many smaller impact craters have since formed. This is a region that is certainly the result of some form of geologic activity occurring after the original crater formation on Dione, again an indication that these objects did not die at the time they were formed but remained active for some time.

It is also possible that the white wispy areas seen over a



Tethys has a valley, visible here down the right half of the satellite, which is about 600 miles long and about 30 miles wide. Like the white, wispy regions on its twin, Dione, this is indicative of internal stresses since formation.



A unique feature of Mimas is an enormous crater more than 80 miles in diameter and three to six miles deep. The central peak is clearly visible, and there are also many smaller, bowl-shaped craters like those on Tethys.

major part of the surface of Rhea and Dione are really very extensive fracture systems. The white is frost — a very white, bright frost of water that has evolved from the interior. This is not at all in keeping with the idea of a very simple, geologically uninteresting iceball.

Tethys has a 600-mile-long valley, perhaps 30 miles wide, that is also likely the result of some kind of internal stresses. Tethys is also cratered, although the craters tend to look more bowl-shaped than the craters on Dione and Rhea. The average density of Tethys is very near that of water ice.

Enceladus, closer yet to Saturn, is only about 300 miles in diameter. We had thought that Enceladus, even though it's small, might still be warm and that perhaps the rock had separated and formed a core. We expected that the surface might be more like that of Europa at Jupiter, that is, a smooth surface, kept young by tidal heating effects induced by other satellites. Unfortunately we did not observe Enceladus very well with Voyager 1. However, an image with the same resolution as one of Tethys that reveals enormous craters shows none on Enceladus. This certainly suggests that Enceladus might not have any substantial cratering. Voyager 2 will fly much closer to Enceladus and may be able to determine whether or not Enceladus has been recently thermally active, kept warm by tidal effects or other not yet identified processes.

Mimas is almost the same size as Enceladus, but we thought it would have a cratered surface and might not be differentiated. Indeed, Mimas has many bowl-shaped craters like those on Tethys, although there are also some linear features, an indication that this surface has also been stressed in some way. Mimas does, however, have one unique feature — a crater about one-third the diameter of the moon itself and three to six miles deep. Simple calculations suggest that if the object that caused this crater had been much larger, Mimas would have fractured into several pieces. Some of the linear features may be the result of the impact rather than the result of an internal heat source. The other satellites exhibit no evidence of a similar spectacular impact which might have caused their surface modifications.

Titan is in a more familiar size class; it's a planet-sized object. It is large enough so that the ice should have melted and the rock should have sunk to the center. Before Voyager, it was known that Titan had an opaque atmosphere containing at least methane. If that is all there had been, the pressure at the surface of Titan would have been about 2 percent of the Earth's surface pressure. On the other hand, something like nitrogen can't be detected from Earth. It had been suggested that the atmosphere could contain enough nitrogen that the surface pressure might be as much as one or two times the Earth's surface pressure and — if the temperature were low enough — there might be liquid nitrogen on the surface, since at one atmosphere pressure nitrogen liquefies at 77 degrees above absolute zero. It was also known that an opaque haze was being produced by the action of sunlight and trapped radiation on the methane. The larger haze particles probably rain down on the surface, possibly forming a layer several thousand feet thick of frozen organic ices, the result of the photochemistry occurring in Titan's atmosphere.

As expected, Voyager's cameras could not peer through the haze, but the haze layer was somewhat brighter in the southern hemisphere than in the northern, which had a dark polar hood. The difference between the north and south is probably a seasonal one. Saturn and Titan are tilted on their axes just as the Earth is — in fact, more so than the Earth. The Titan year is about 30 Earth years, and when Voyager arrived at Titan, it was the equivalent of the beginning of April; in other words, southern summer had gone and northern summer was approaching.

Since not much could be seen visually, Voyager's other instruments provided much of the key information about Titan. Several experiments depended on the fact that the spacecraft was to fly very close to Titan — about 2600 miles above the thick haze layer. It flew through the magnetospheric wake, thus named because as Saturn's magnetic field and particles rotate with Saturn, they flow past Titan, forming a wake. Voyager also flew behind Titan to view the sunset through the atmosphere, and then the spacecraft disappeared behind the satellite as viewed from Earth, making it possible to probe very deeply into Titan's atmosphere with the spacecraft radio signals.

These measurements located Titan's surface almost 150 miles below the haze layer. The pressure at the surface is about one and one-half times that of the Earth's atmosphere, and the bulk of the atmosphere is nitrogen. The temperature at the surface is $-294$ degrees Fahrenheit, or 93 K. That is interestingly close to the temperature at which methane can exist simultaneously as a liquid, a solid, and a gas — the triple point. On Earth, water is near its triple point so that it can either rain or snow. In this sense, methane is the water of Titan. Depending on the surface temperature, or perhaps on the season or latitude, the methane on Titan's surface could be solid methane ice; it could be liquid methane in lakes and rivers; or the surface could be a desert with no methane at all. Higher in the atmosphere the temperature drops, just as it does here on Earth, resulting in the formation of clouds of methane ice, from which methane will rain, or more likely snow, back onto the surface.

Still higher in the atmosphere it is somewhat warmer because of the absorption of sunlight by the thick haze layer. Other thinner haze layers occur at altitudes up to 500 miles above the solid surface. Some of these layers are molecular, that is, they're not composed of small particles, but of individual molecules of organic material produced from the methane and nitrogen in the atmosphere.

The chemistry that produces these organic molecules is of special interest. When fast electrons, which are carried along in Saturn's rotating magnetosphere, collide with the top of Titan's atmosphere, they excite the nitrogen molecules which then emit ultraviolet light, which was detected by Voyager. The fast electrons, however, can also break the nitrogen molecule into individual nitrogen atoms or into electrically charged ions. Either the atom or the ion can subsequently combine with methane to produce hydrogen cyanide (HCN), which is a building block for amino acids. Similar chemistry may have occurred here on Earth, eventually leading to the formation of life. Undoubtedly the process does not progress nearly as far on Titan because the temperature is so cold. The HCN itself is further affected by sunlight, which can cause it to polymerize and form large haze particles. So it is possible that the orange haze on Titan is a haze of HCN or some compound related to it. Not all of the nitrogen reactions result in HCN, however. Some of the nitrogen ions are stripped away from the top of Titan's atmosphere, forming a long plume that is carried away by Saturn's rotating magnetosphere.

Voyager made a number of other discoveries about the magnetic field and trapped radiation belts comprising Saturn's magnetic field. The discovery of periodic radio bursts from Saturn's rotating magnetosphere provides the first accurate measurement of the length of a Saturn day — 10 hours, 39.4 minutes. As the magnetic field rotates, it carries with it a plasma of electrically charged ions from Titan, the icy satellites, and the rings, forming an equatorial disc about Saturn. There is also a tenuous torus of hydrogen, which glows with ultraviolet light, filling the region between the orbits of Rhea and Titan.

These are just the highlights of what we are beginning to understand from Voyager 1. The spacecraft is now on its way out of the solar system. It has finished exploring the planets, but it hasn't finished exploring the solar system. Voyager's trajectory will take it up out of the plane of the planets toward the heliopause, where the solar wind, which is blowing a bubble in the interstellar medium, ceases. We don't know exactly where that is; it may be anywhere from 30 to 60 astronomical units or more from the sun (the Earth is at 1 astronomical unit). By 1990 Voyager 1 will be some 40 astronomical units from the sun, and it is possible that somewhere in that time Voyager might leave the solar wind behind and for the first time enter the interstellar medium consisting of material coming from other stars. We expect that even before Voyager reaches the end of the solar wind, the cosmic ray investigation led by R. E. Vogt, professor of physics at Caltech, will begin to detect for the first time the low-energy cosmic rays coming from nearby regions in the Galaxy.

As far as the planets are concerned, Voyager 2 will be taking a very close look at Tethys and Enceladus in August. It will also investigate the braided F-ring, taking stereo images in order to determine whether it is in a two-dimensional or a three-dimensional braid. We will investigate the structure of the braiding in the vicinity of the shepherding satellites and search for any changes in the braiding when in Saturn's shadow, as might be expected if electrostatic charging is important. Other new investigations will include observations of a star through the rings, which should provide detailed information on the location and width of each of the hundreds of ringlets.

Although designed just for the four-year mission to Saturn, Voyager 2 will nevertheless head toward Uranus, arriving there in 1986, when the planet's spin axis is pointed at the sun. Uranus is tilted on its side — a most unusual configuration. The nine known narrow F-type rings and five icy satellites form a bull's-eye pattern around Uranus, but if Saturn is any indication, there is much more waiting to be discovered. Extending our hopes still further, Voyager can swing past Uranus toward a 1989 encounter with Neptune and its satellite Triton, a possible twin of Titan.

In the meantime, tune in again in August for the next program from Saturn. □