CHAPTER 4

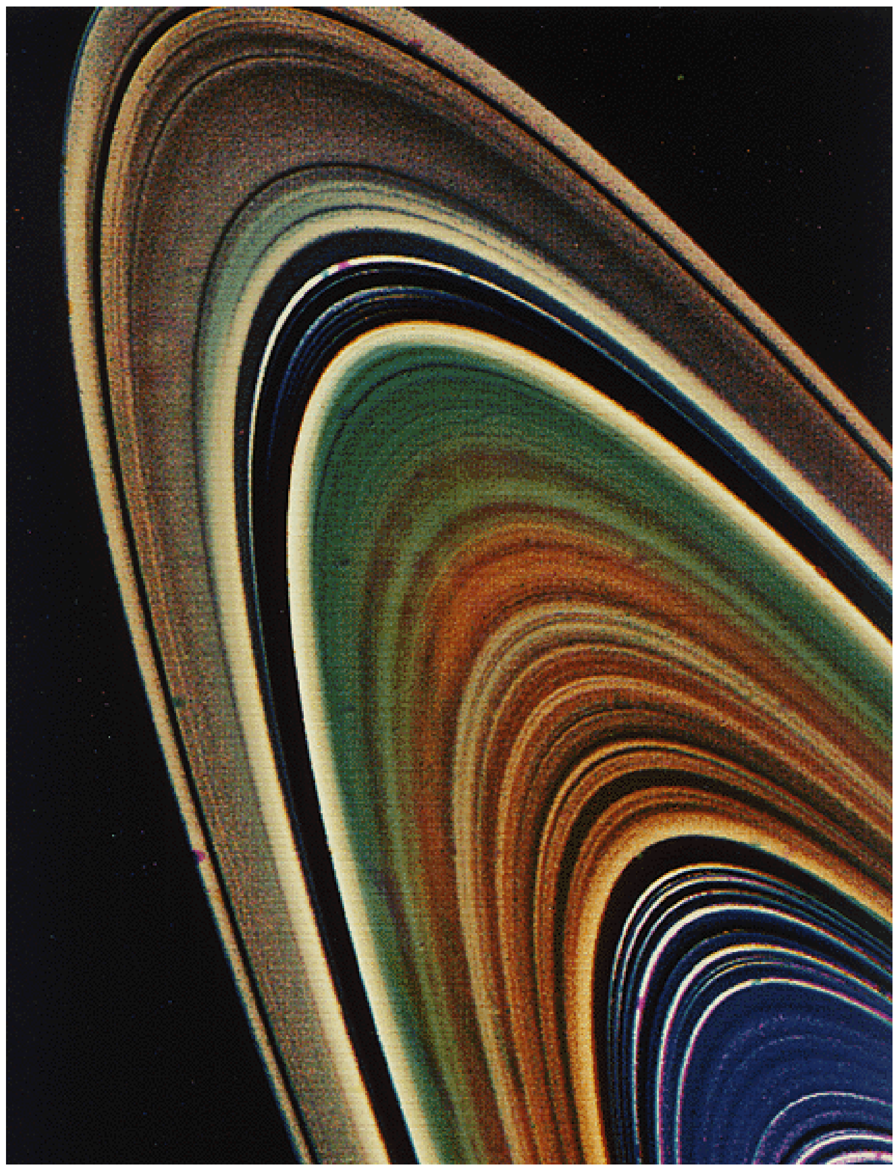
Those Magnificent Rings

Galileo first pointed his tiny telescope at Saturn in July of 1610. Since then, the rings of the giant planet have become one of the great, enduring mysteries of our solar system. Even today, those magnificent rings are the most requested object for viewing at any public telescope session. While the beauty of the rings is universally known, the mystery of their existence has challenged the explanations of astronomers for four centuries.

Historical Background

For reasons that are lost to us, Galileo initially paid little attention to Saturn beyond his declaration that it was a triple planet. To him and other early viewers, the nature of the rings was masked by the poor quality of the telescopes of the time. After his initial observations, Galileo seemed to lose interest in Saturn and did not view the planet again for two years.

When Galileo again chanced to look at Saturn, in 1612, the planet's appearance had totally changed. Saturn no longer seemed "triple," but appeared as a single "ball," similar to the appearance of Jupiter in his small instrument. The puzzle of Saturn, which would grow for centuries, had begun to take shape.



This enhanced Voyager 2 image shows some hints of possible variations in the chemical composition of Saturn's rings.

In 1616, when Galileo once again returned to his observations of Saturn, the planet had changed again! The features he had initially seen as separate bodies now had an entirely different appearance; he termed them "ansae" or "handles."

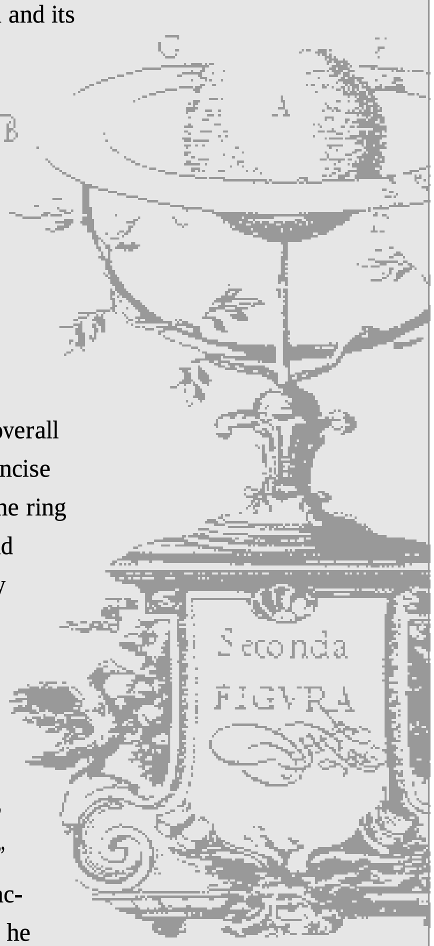
Ring Nature

Once the changing appearance of Saturn had been explained by a ring around the planet, the next question

HUYGENS' HANDLE ON THE RINGS

Following Galileo's characterization of Saturn's "handles," various observations were made by astronomers until 1655, when Christiaan Huygens turned a telescope of far better quality than Galileo's toward the planet and discovered its large moon, Titan.

Within a year, Huygens had arrived at a theory to explain some of the mystery regarding the continually changing appearance of Saturn – he correctly asserted that Saturn was surrounded by a disk or ring whose appearance varied because of the inclination of Saturn's equatorial plane and the planet's orbital motion around the Sun. Shown here is the model of Saturn and its rings used by the Accademia del Cimento to test Huygens' hypothesis.



Huygens had some details about the rings wrong, but his overall theory was a concise explanation of the ring phenomenon and was soon widely accepted. By 1671, when Huygens' theory correctly predicted the rings' "disappearance," his model was accepted as fact – he indeed had grasped the "handle" on the rings.

to occupy astronomers concerned the nature of the ring, or rings. Were the rings solid, or were they a swarm of tiny satellites in orbit, as suggested in 1660 by Christiaan Huygens' close friend, Jean Chapelain? The accounts of various observers caused adjustments to Huygens' theory, and the observations of Jean-Dominique Cassini added information to the scientific debate.

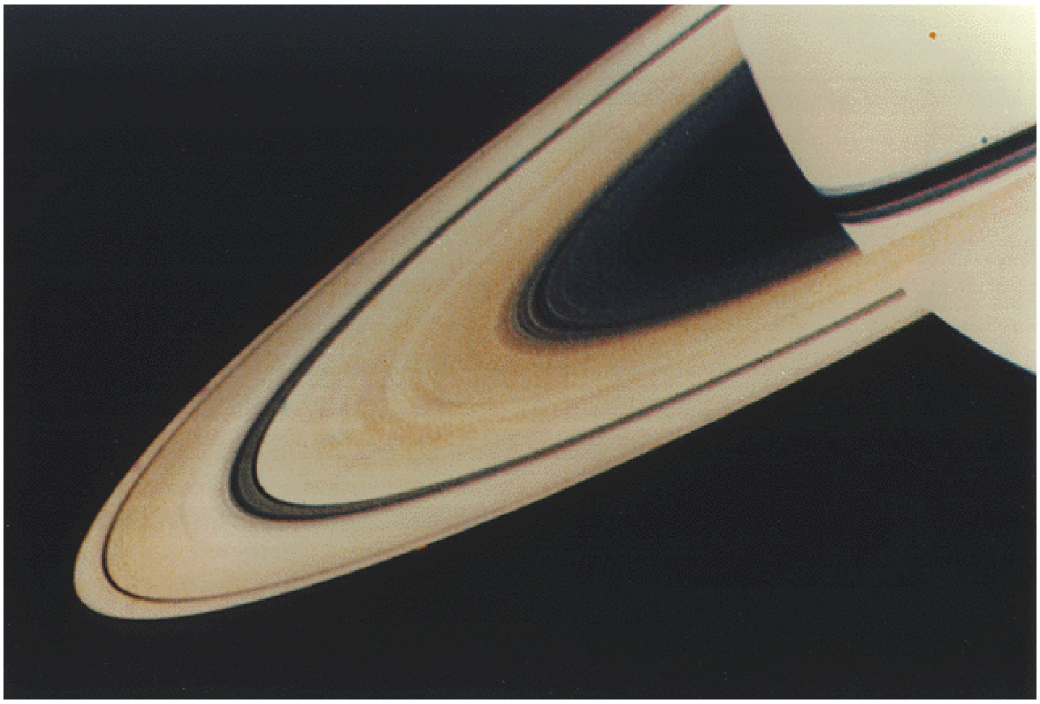
Cassini noted that the brighter and dimmer portions of the rings were separated by a dark band, which he interpreted to be a "gap." This meant that there were actually two rings, but the thought of two solid spinning disks around Saturn was a bit much for astronomers to believe. The "solid disk" theory began to lose its appeal. Instead, by the beginning of the 18th century, the notion that Saturn's rings were actually a swarm of tiny, orbiting satellites gained wide favor in the astronomical community.

During the 19th century, as telescope quality improved, astronomers made numerous studies of Saturn's rings. The quality of observations also generally improved — the matter of the rings' nature was being addressed. In 1857, James Clerk Maxwell put forth a now-famous theory about the nature of the rings, attributing them to swarms of particles and providing a good explanation for the existence of such a system. In 1866, Daniel Kirkwood noted that the Cassini division (or gap) lay at an orbital resonance point[1] with the orbit of Mimas; he later noted that the Encke division also lay at a resonance point.

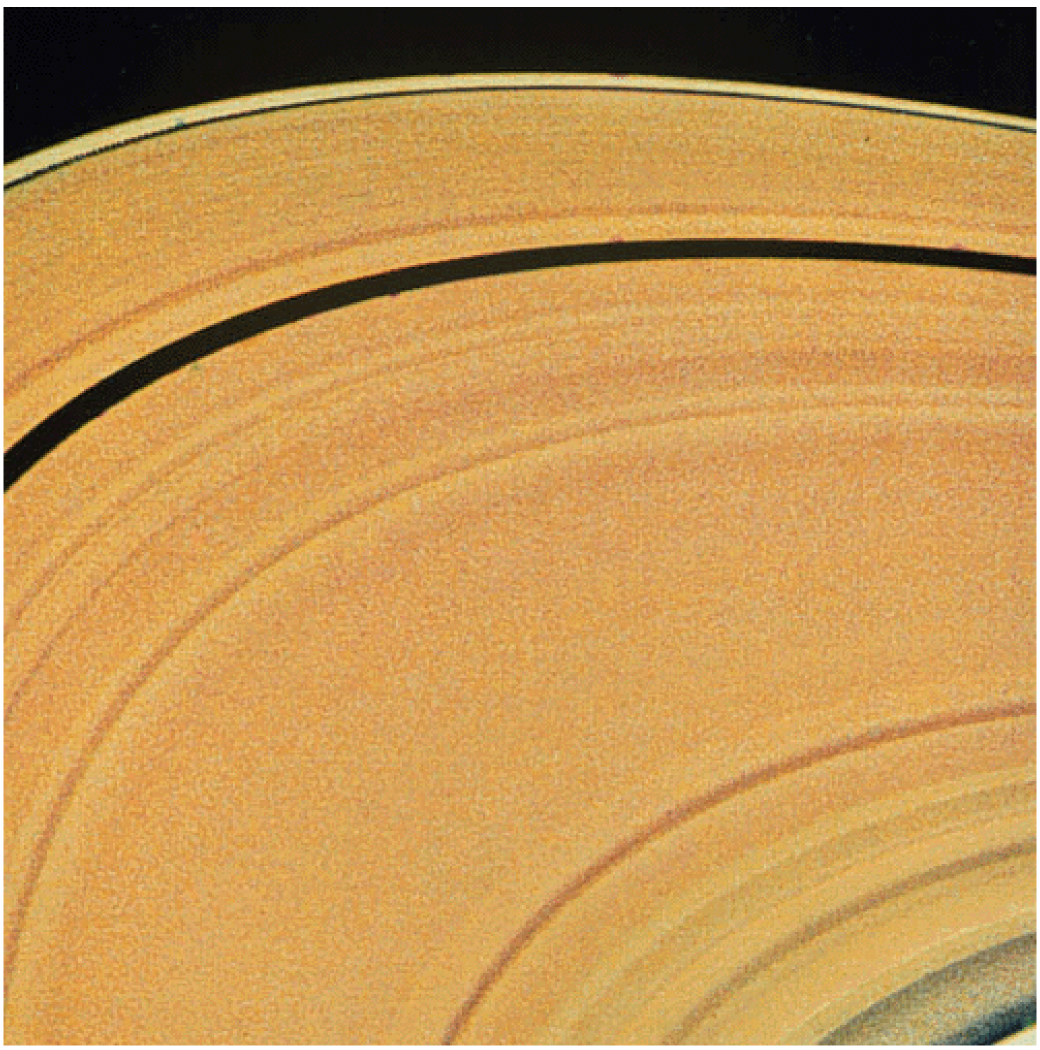
In 1872, James Keeler noted a narrow gap in the outer A-ring, termed by later observers as the Keeler gap[2]. In 1889, E. E. Barnard made measurements of an occultation of Iapetus by the translucent C-ring, finding it to be a semitransparent ring of nonuniform optical density. In 1895, Keeler proved using spectroscopic evidence that the rings were composed of swarms of particles moving in Keplerian orbits, thus validating Maxwell's theory. In 1908, Barnard made a series of observations at the time of Earth's passage through Saturn's ring plane, concluding that the Cassini division was not devoid of particles.

Over the years, interesting features noted by Earth-based astronomers were not readily subject to verification. In fact, many observations about Saturn remained in dispute until the first robotic probes — Pioneer 11, Voyager 1 and Voyager 2 — flew close to the planet. Viewing Saturn from Earth involves peering through a turbulent atmosphere. Visual acuity varies from person to person: what one observer glimpses for a few seconds now and then might never be seen by another observer at a less favorable observing site or with less acute eyesight.

Even the advent of photography in the late 19th century did not improve discovery verification, since photographic studies were more subject to the woes of looking through Earth's turbulent atmosphere. Only the passes by Pioneer and Voyager



Voyager 1 captured this striking image of Saturn and its rings, with the rings cutting a dark shadow across the planet.



This false-color image of Saturn's outer A-ring was constructed from green, violet and ultraviolet frames. Voyager 2 captured the image on August 23, 1981.

crystallized centuries of Saturn observations, almost instantly sorting observational fact from fiction — just as the Mariner flybys shattered the myths of Martian canals and civilizations.

Ring Structure

Large-Scale Features. Viewing Saturn and its rings through a modest telescope easily allows us to see that the ring system is divided into several visually different radial zones. The outer zone (visible to an Earth observer) is known as the A-ring, while the brighter, inner zone is known as the B-ring. Between these two zones we can sometimes see the gap known as the Cassini division; on an exceptional viewing night, we may see an inner, semitransparent ring, the C or Crepe ring.

This view of the rings, while modest, nevertheless introduces us to the system's unexplained features. Why are there several morphologically distinct rings? Beyond the A, B, C and E-rings, which can be seen or imaged from Earth-bound telescopes, Saturn has several other distinct rings — the D, F and G-rings — detected in the images from Pioneer and Voyager.

The mysteries of Saturn's rings lie at an even more fundamental level: Why are the rings there at all? How did the rings form? How stable is the ring system? How does the system maintain itself? So far, we have only bits and pieces of answers and much speculation about these questions.

THE RINGS OF SATURN

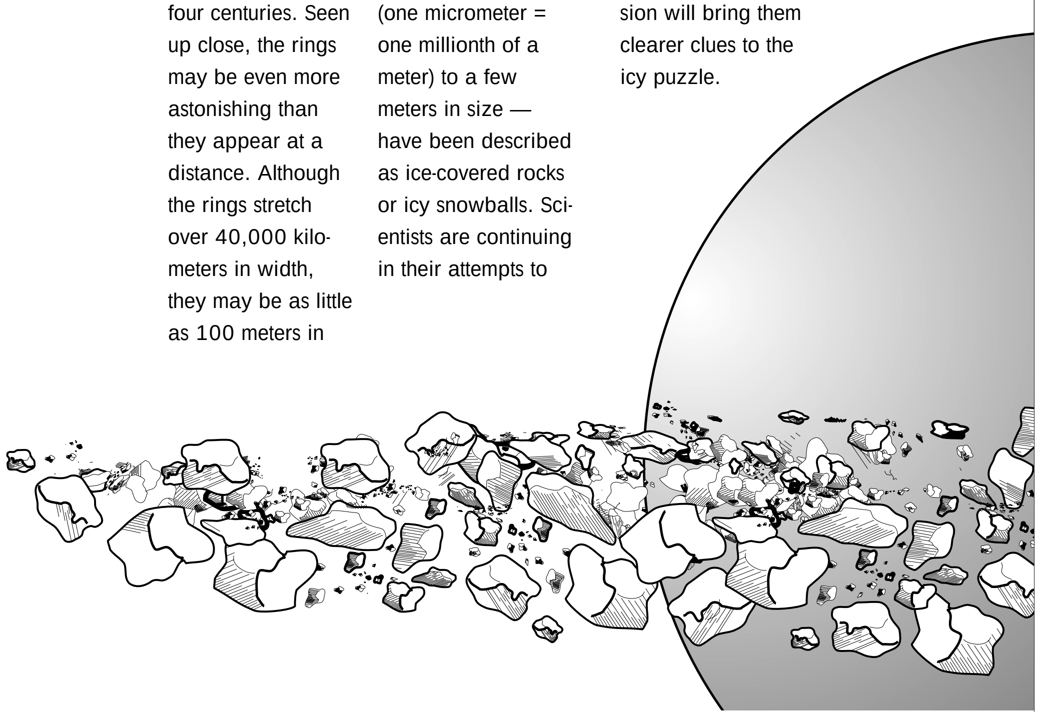
Ring	Distance, kilometers*	Width, kilometers
D	66,970	7,500
C	74,500	17,500
B	92,000	25,400
A	122,170	14,610
F	140,180	50
G	170,180	8,000
E	180,000	300,000

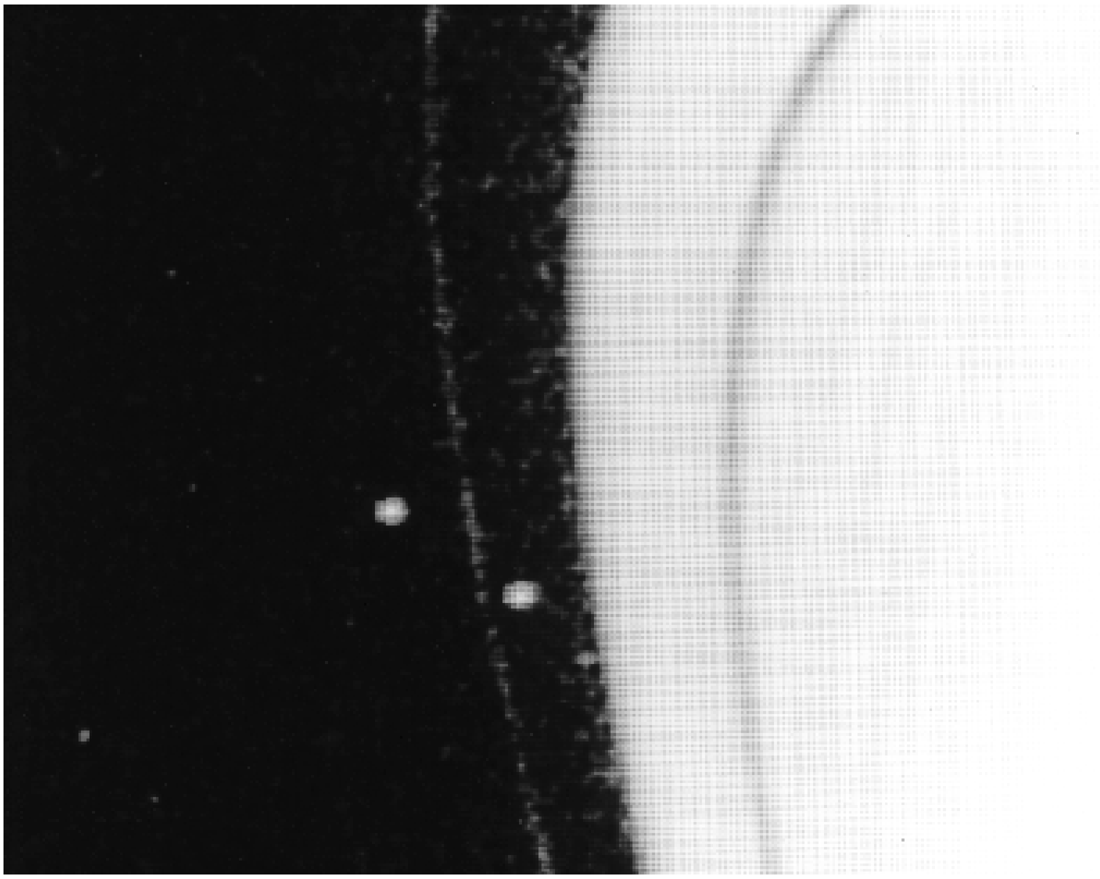
* *Distance from Saturn to closest edge of ring.*

Smaller-Scale Features. As Pioneer and Voyager moved closer to Saturn, the spacecraft captured images that made clear the features glimpsed over the centuries, as well as many previously unseen features. Pioneer found a new ring feature (the F-ring) outside the A-ring, which became an object of major interest when Voyager later arrived. The fields and particles sensors on Pioneer 11 showed the possible presence of satellites in the vicinity of the new F-ring. This ring proved to be particularly interesting — it is a narrow ring, and the satellites that (as we now know) maintain the ring in position were the first proof of a theory put forth in 1979 to explain the narrow rings of Uranus.

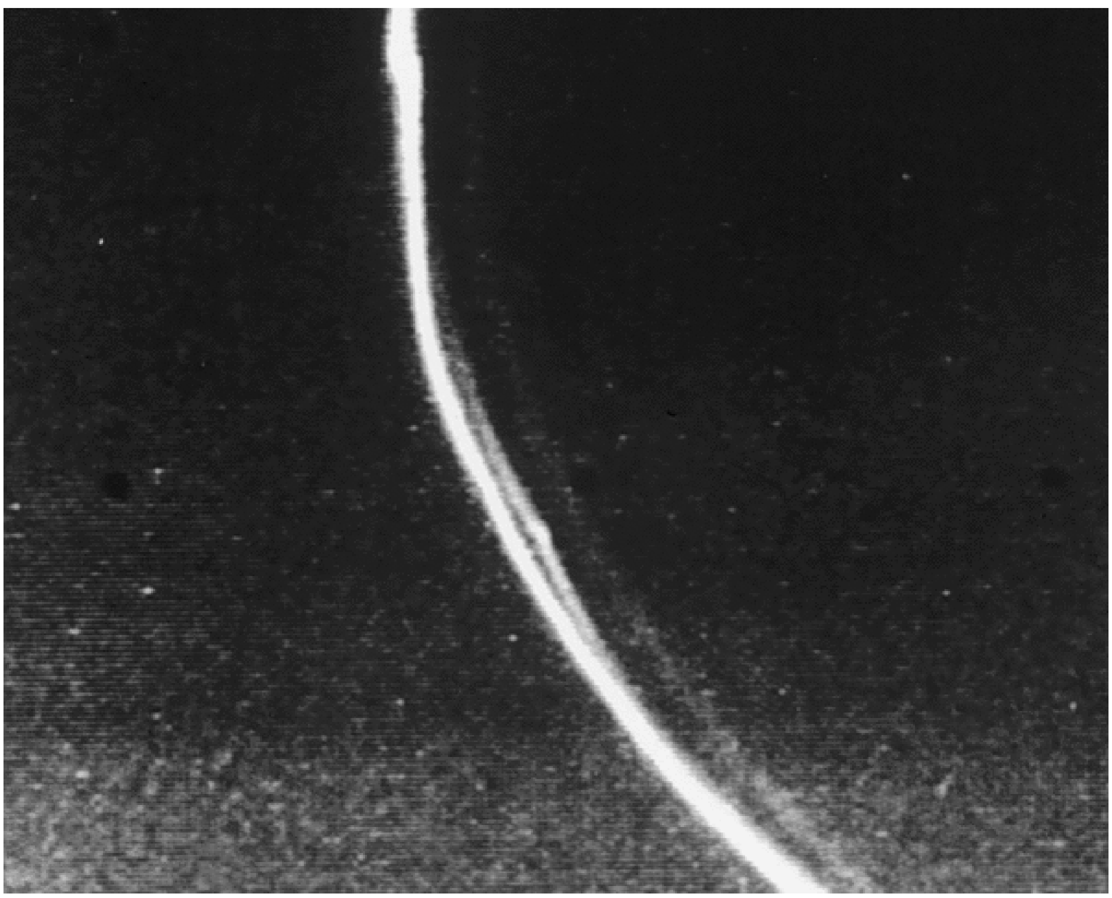
SATURN'S FLYING SNOWBALLS

Saturn's rings have intrigued scientists on Earth for nearly four centuries. Seen up close, the rings may be even more astonishing than they appear at a distance. Although the rings stretch over 40,000 kilometers in width, they may be as little as 100 meters in thickness. The ring particles — from a few micrometers (one micrometer = one millionth of a meter) to a few meters in size — have been described as ice-covered rocks or icy snowballs. Scientists are continuing in their attempts to analyze ring composition, hoping that the Cassini–Huygens mission will bring them clearer clues to the icy puzzle.





Prometheus and Pandora, two tiny satellites, shepherd Saturn's F-ring, which is multistranded and kinked in places.



This Voyager 1 image clearly shows the kinky, braided structure of the F-ring.

Voyager's high-resolution azimuthal studies of the new F-ring showed that the ring was even more unusual than expected: It comprises a number of strands that appear to be intertwined and braided in some places, and kinked in other locations. While the gravitational effects of nearby moons may be responsible for some F-ring attributes, they do not account for the complex structure that Voyager discovered. Continuing studies of Voyager images over the years have unraveled more of the complex properties of this unusual ring.

The possibility of numerous, small satellites occurring within Saturn's ring system was a puzzle the Voyager mission had hoped to solve. Voyager's best-resolution studies of the ring system were aimed at revealing any bodies larger than about 10 kilometers in diameter; nevertheless, only four moonlets — Atlas, Pan, Prometheus and Pandora — were found in the images. Only one, Pan, was located in the main ring system.

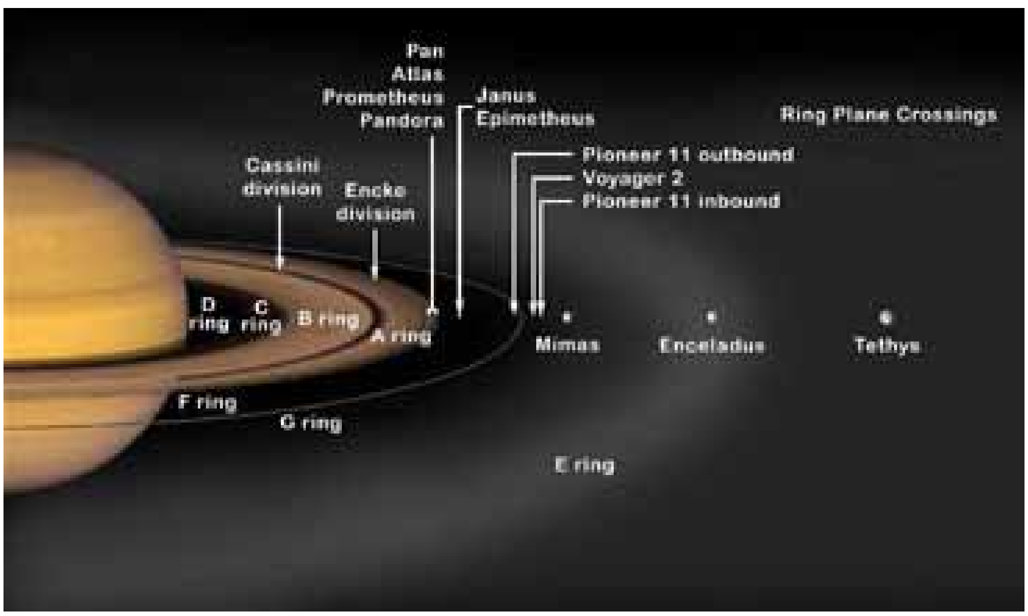
The Voyager high-resolution studies did, however, detect signs of small moonlets not actually resolved in the images. When a small, dense body passes near a section of low-density ring material, its gravitational pull distorts the ring and creates what are known as "edge waves."[3] While the high-resolution, azimuthal coverage of the ring system is a time-consuming endeavor, such studies are the only means of detecting these waves and thereby finding satellites too small to be seen in images. Soon, four years in orbit will provide Cassini with many good opportunities for conducting azimuthal imaging studies.

Occultation Experiments

Cassini will be able to perform a number of the experiments that Voyager used to detect other gravitational effects on Saturn's ring material. One experiment, termed an "occultation experiment," involves watching as light from a star (a stellar occultation) or the radio beam from the spacecraft (a radio occultation) passes through the ring material to see how the beam is affected during the occultation. As the beam passes through the ring material, it may be attenuated or even extinguished. These experiments provided an extremely high-resolution study of a single ring path with resolutions up to about 100 meters.

SATURN'S CROWN JEWELS

Saturn's rings are easily the crown jewels of the entire solar system. And the variety of rings is staggering; the count in high-resolution images suggests anywhere from 500 to 1,000 separate rings! Named in order of discovery, the rings' labels do not indicate their relative positions. From the planet outward, they are known as D, C, B, A, F, G and E.



In the stellar occultation experiment, the Voyager 2 spacecraft had a single opportunity to observe as light from a star was occulted by the ring system. As the light passed through the rings, it was attenuated and extinguished by the particles comprising the system. The velocity of the spacecraft, the brightness of the star, the sensitivity of the instrumentation and the sampling rate of the instruments provide the limitations for such stellar occultation experiments.

The primary instruments used to conduct the stellar occultation study were Voyager's photopolarimeter and ultraviolet spectrometer, with the photopolarimeter providing the higher resolution data set. Resolving features as small as about 100 meters, the stellar occultation experiments detected many small-scale ring structures and found that the F-ring was far more complex than images had suggested. The data set, furthermore, showed that the B-ring was quite opaque in many regions and confirmed that the Cassini "division" was not at all empty. It also provided a direct measurement of the maximum thickness of the ring system in several locations, finding it to be much less than 100 meters thick.

In the radio occultation experiment, Voyager 1 had a single opportunity to watch as the spacecraft's radio beacon was occulted by the ring system. As this radio signal passed through the ring material, its signal was also attenuated. The antennas of the Deep Space Network received the attenuated signal, allowing scientists to study the complex data being returned. While the radio-science data set was complicated to process and interpret, it yielded information on particle size distribution in the ring system not available from stellar occultation studies. From the radio-science data set, we know something of the size distribution of the larger particles in the ring system. We know that much of the ring mass is in particles from a few centimeters to a few meters in diameter; boulders more than 10 meters in diameter do not comprise much of the mass of Saturn's ring system.

Both occultation experiments described here detected features in Saturn's rings caused by the gravitational effects of the planet's satellites. Locations where gravitational resonance effects had partially cleared material were identified by these experiments and are also visible at lower resolution in imaging data. While the existence of resonances had been recognized since 1866 — when it was pointed out that the Cassini division lay near a gravitational resonance point — the extent to which the structures occur was largely unexpected.

At these resonances, gravitational-wave effects were detected in the photopolarimeter, ultraviolet spectrometer and radio-science occultation data sets — known as density and bending waves — that are similar in behavior to the arms of spiral galaxies. While some of these structures were later detected in the imaging data, the high-resolution data sets of the photopolarimeter, ultraviolet spectrometer and radio-science experiments provided the details that allowed Voyager science teams to derive information about the mass, density and viscosity[4] of the ring material in their vicinity. Much of the fine structure of the A-ring is well-explained by such gravitational resonances with satellite orbits. However, the resonance theory does not provide a universal solution and much of the structure of the B-ring is left unexplained.

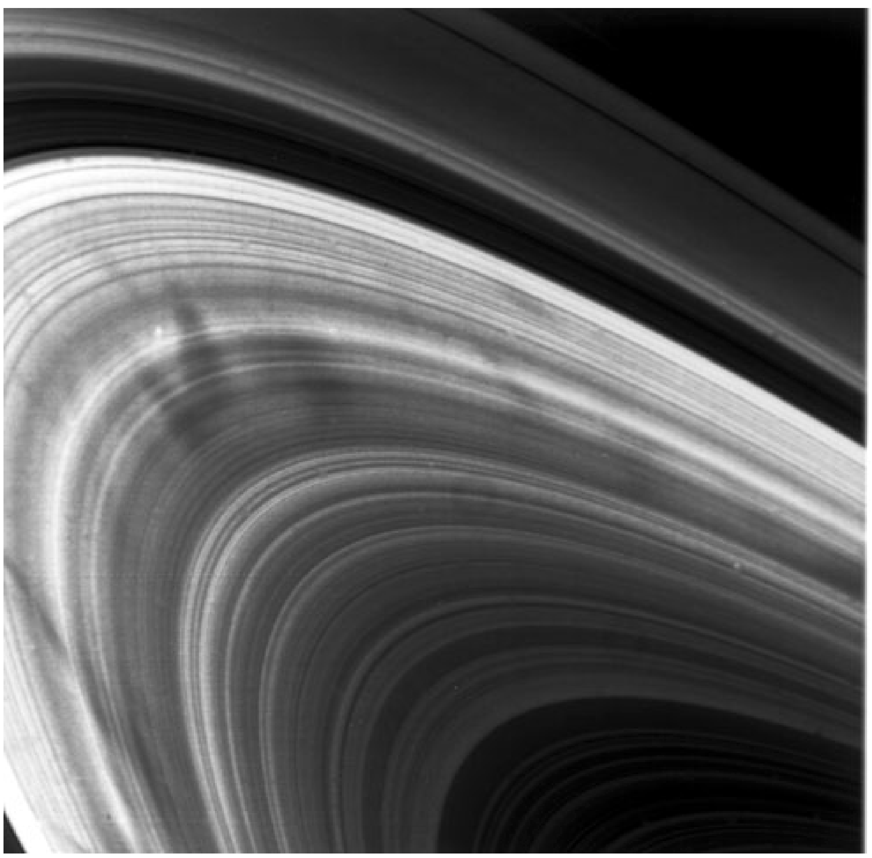
The occultation results, along with imaging studies, showed that a great many of the narrow ringlet features at Saturn are slightly eccentric — not circular in shape — and that these eccentric ringlets lie embedded in the mass of nearly circular rings that constitute the majority of Saturn's ring system. These same studies also showed that many small ringlets are asymmetrical in structure and that there are very few truly empty "gaps" in the ring system.

Results from the Voyager experiments provided a wealth of information to explain some physical properties of Saturn's rings, but at the same time, they also created many mysteries that were unexpected and not understandable through Voyager data. For instance, Voyager data did not detect the number of moonlets we expected. Are these moonlets non-existent or just not yet discovered? Cassini will have far more time to perform ring searches and will provide higher resolution data sets, both required to answer this question.

Ring Spokes

As Voyager approached closer to Saturn, images began to show dark, radial structures on the rings. While these features had been sighted by Earth-based observers over the decades, the Voyager images showed the "spokes" in great detail, allowing them to be studied as they formed and rotated about the planet. Spokes seemed to appear rapidly — as a section of ring rotated out of the darkness near the dawn terminator — and then dissipate gradually, rotating around toward the dusk ring terminator. A spoke's formation time seemed to be very short; in some imaging studies one was seen to grow over 6000 kilometers in distance in just five minutes.

As it passed from the day side to the night side of the planet, Voyager provided unique views of Saturn's rings and was able to observe the rings and spokes in forward-scattered light where they appeared as far brighter features than in backscattered light. This light-scattering property showed that the spokes were largely composed of very small, micrometer-sized particles.



The numerous "spoke" features in the B-ring are evident in this image obtained by Voyager 2.

The spokes in Saturn's rings form at the distance from Saturn where the rotational speed of the ring particles matches that of the planet's magnetic field lines. Further studies of this possible interaction revealed a link between the spoke formation and a region on the planet associated with intense long-wavelength radio emissions (now referred to as the Saturn kilometric radiation, or SKR, zone). All these studies pointed to a sizable interaction between the ring system and Saturn's electromagnetic fields. But what was it? Once again, Voyager had provided a tantalizing tidbit of information, but had left a riddle.

Ring Particle Properties

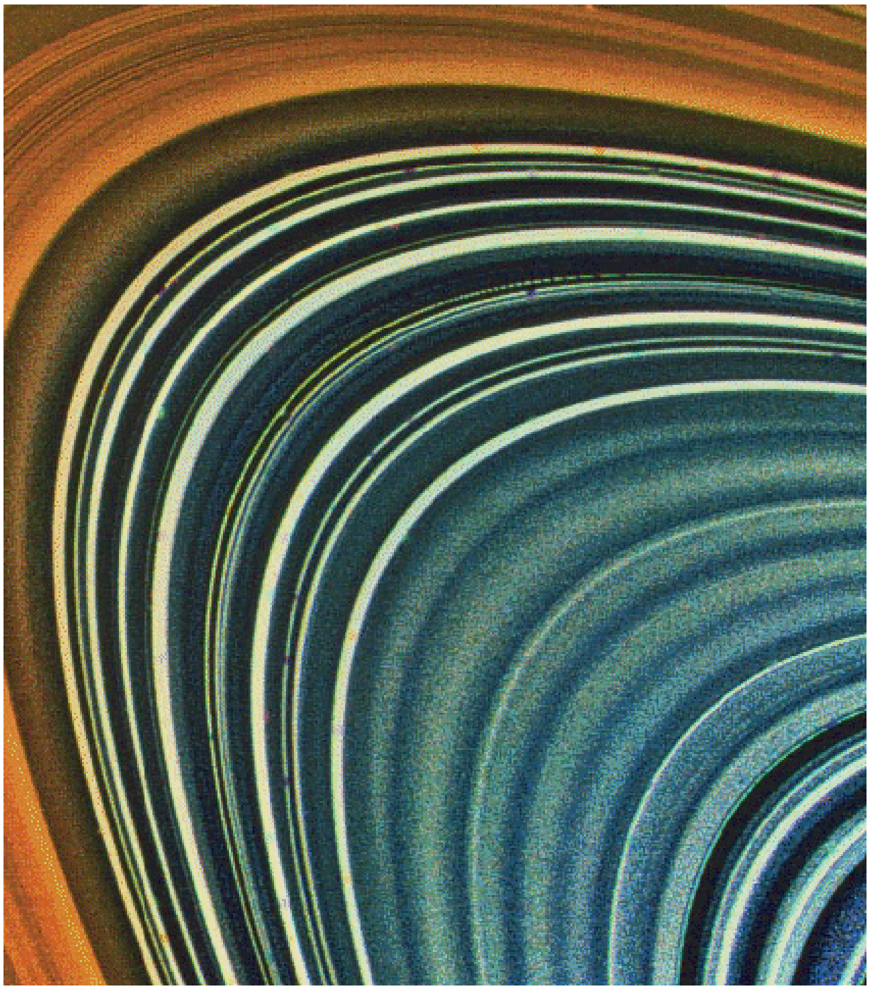
The Voyager trajectories allowed the rings to be viewed from a much wider range of angles than could ever be achieved by Earth-based observers. This allowed for extensive observations of the light scattering, or photometric, properties of the rings. The proximity of the spacecraft to Saturn also provided for higher resolution photometric and spectral studies than could ever have been achieved by Earth-based observers. These studies yielded a great deal of information about the nature of the ring particles and the composition of the rings.

Observations in forward-scattered light made while the spacecraft was on the dark side of the planet showed that some areas of the rings were much brighter in forward-scattered light than others. Small particles in the micrometer-size range are much more efficient in producing forward scattering than are larger particles, so this tells us that these areas of the rings have an abundance of small, micrometer-size particles. The D, E, F and G rings all show such forward-scattering properties as do the spokes of the B-ring. These data, combined with ring occultation data from the photopolarimeter, ultraviolet spectrometer and radio-science experiments, give us some information about the variation of particle-size distribution across Saturn's ring system. Cassini will have the opportunity to conduct extensive studies of these diffuse rings and their particle distributions.

Ring Composition

Ground-based infrared spectral studies of the A and B rings show that they are composed largely of very nearly pure water ice. The spectral characteristics of the rings are also very similar to those of several of Saturn's inner satellites. The extended wavelength range over which Cassini will be able to make spectral measurements will yield information on both the nature of the chemical contaminants in the rings' water ice as well as on the relationship between ring and satellite composition.

Studies of the color distribution (as a sign of compositional variation) in the main rings show that the ring system is not completely uniform in its makeup and that some sorting of materials within A and B rings exists. Why such a nonuniform composition exists is unknown; Cassini data will provide some clues toward solving this problem. The other, diffuse rings



This false-color image of Saturn's B and C rings reveals fine details and subtle color differences.

of Saturn are much more difficult to study in this manner, but we do know that the E-ring is somewhat bluish in color — and thus different in makeup from the main rings. Speculation exists that the moon Enceladus is the source of E-ring material, but this is unconfirmed.

Since ring particles larger than about one millimeter represent a considerable hazard to the Cassini spacecraft, the mission plan will include efforts to avoid dense particle areas of Saturn's ring plane. The spacecraft will be oriented so as to provide maximum protection for itself and its sensitive instrumentation packages. Even with such protective steps, passage through the ring plane will allow the Cassini particle measurement experiments (the Cosmic Dust Analyzer, the Ion and Neutral Mass Spectrometer and the Cassini Plasma Spectrometer) to perform important studies of the particles making up the less dense regions of the Cassini ring plane. Such measurements could provide insight into the composition and environment of the ring system and Saturn's icy satellites.

Voyager 1 looked back on November 16, 1980, four days after flying by the planet, to capture Saturn and its spectacular rings from this perspective.

Formation and Evolution

A century after their discovery, the origin of Saturn's rings was a point of speculation. Then, for many years, the matter was actually thought to be well understood. Today's view is that the origin of those magnificent rings involves a complex set of issues. The size, mass and composition of the rings make their formation and evolution rather difficult to explain.

Among the early notions about the rings' origin was a theory by Edouard Roche. He suggested that the rings were fragments left over from a moon that had at one time orbited Saturn. This moon had broken up, Roche explained, because of the tremendous stresses placed upon it by Saturn's huge gravitational field.

The Roche theory does not hold up well, however, under scrutiny. For instance, did the rings form out of the initial solar system nebula, or after one or more satellites were torn apart by Saturn's gravity? Moreover, if the rings were the result of the numerous comets captured and destroyed by Saturn's gravity, why are Saturn's rings so different in nature from the rings of the other giant planets? Over their lifetime, the rings must have been bombarded continually by comets and meteors — they should have accumulated a great amount of carbonaceous and silicate debris — yet their composition seems almost entirely to be water ice.

Another issue concerns the stability of the ring system. The effects of torque and gravitational drag, along with the loss of momentum via collisional processes should have produced a system only one-tenth to one-hundredth the age of the solar system itself. If this hypothesis is correct, then we cannot now be observing a ring system around Saturn that formed when the solar system coalesced.

In fact, Saturn's rings — as well as the rings of all the other large planets — may have formed and dissipated many times since the beginning of the solar system. If anything, we may infer that ring systems are in a constant, steady state of renewal and regeneration. We are quite likely a long way from understanding all the processes and dynamics of ring formation, renewal and evolution.

In conducting an array of ring studies, the Cassini mission will ultimately focus on four critical questions: How did the rings form? How old are the rings? How are the rings maintained? What are the dynamics and relationships of the rings to Saturn, its satellites and its electromagnetic fields?

In attempting to answer these questions, whereas the Voyager spacecraft had only a few days close to Saturn's rings — time only enough to suggest some tantalizing clues — Cassini will have several months to observe the rings in detail and return enough data to substantially increase our knowledge base.

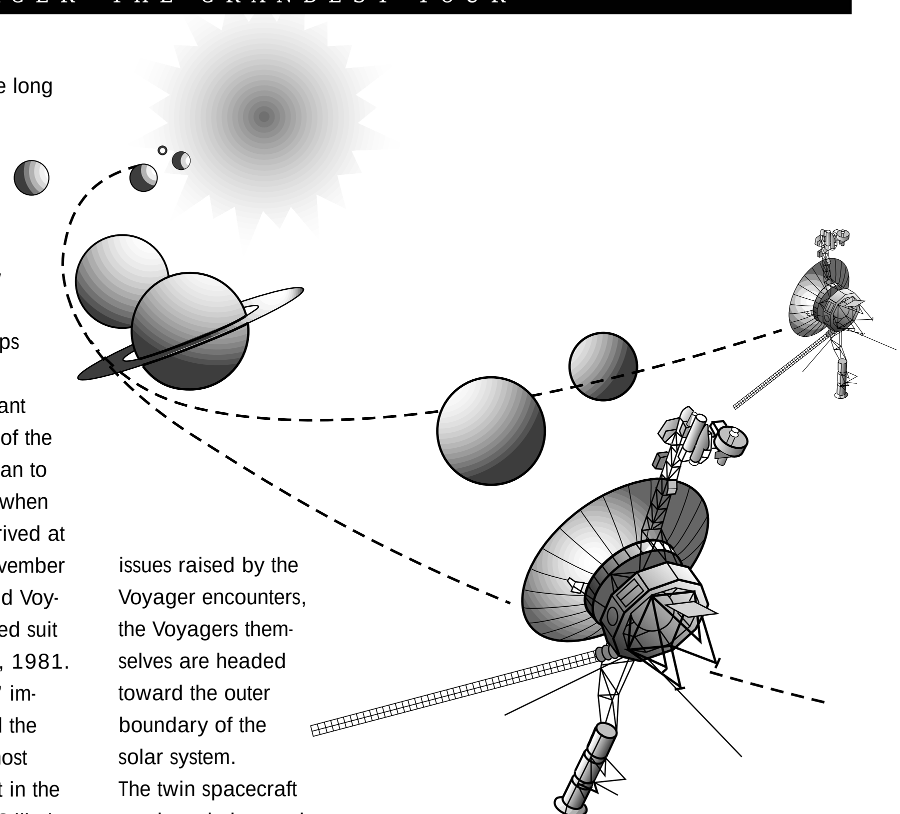
Voyager Legacy, Cassini Mission
Information about Saturn's rings "discovered" by the Voyager mission — which was then studied and documented — was not entirely new to Earth-bound astronomers. Ring gaps, narrow rings, spokes, diffuse rings, sharp ring edges, satellite resonances — these were all features seen or inferred before. Nevertheless, scientists were stunned by the sheer abundance of these features on every scale once Voyager began returning actual, high-resolution images of the ring system.

As more and more data arrived on Earth, one thing was increasingly clear: Rather than solving the mystery of Saturn's rings, Voyager was instead showing us how little we knew about them, even after four centuries of study!

After two decades of studying the Voyager data, and then studying more recent data from the Hubble Space Telescope, scientists have developed a new set of questions for the Cassini mission to investigate when the spacecraft reaches Saturn in 2004. The answers Cassini may find to these questions will help to explain some of the processes in the rings' origin. Scientists are aware, however, that the data Cassini returns will quite probably present us with another round of surprises — and yet more questions.

Early observers were puzzled by the changes that Saturn's rings showed

VOYAGER—THE GRANDEST TOUR



Scientists have long sought to determine what the rings of Saturn are made of, how they got there and what keeps them in orbit around the giant planet. Some of the questions began to be answered when Voyager 1 arrived at Saturn on November 12, 1980, and Voyager 2 followed suit on August 25, 1981. The Voyagers' images revealed the rings as the most exquisite sight in the solar system. Still, the discoveries presented many more new puzzles than solutions.

Now, as Cassini–Huygens prepares to tackle the many issues raised by the Voyager encounters, the Voyagers themselves are headed toward the outer boundary of the solar system. The twin spacecraft continue their grand tour of the solar system in search of the heliopause, the region where the Sun's influence wanes and the beginning of interstellar space can be sensed. The Voyagers have enough electrical power and thruster fuel to operate until at least 2015. By then, Voyager 1 will be 19.8 billion kilometers away from the Sun, and Voyager 2 will be 16.8 billion kilometers away.

from year to year. Now, after centuries of Earth-bound observations followed by spacecraft explorations, scientists do not question if Cassini will find changes in Saturn's ring system. Instead, they wonder what changes the rings have undergone since Voyager last looked in 1981.

Among other things, Cassini will probe the many questions raised by Voyager, and Pioneer before that, about Saturn's rings. In this endeavor, the new spacecraft has several expected advantages over its predecessors. Cassini's science instrumentation covers a broader range of the electromagnetic spectrum and is of greater sensitivity and resolution.

In addition, while Voyager was a mission of discovery into previously uncharted frontiers, Cassini is a focused return visit, designed to address specific issues. Of course, Cassini is also expected to make its own discoveries about Saturn.

The ring system of Saturn — which contains the widest array of attributes of all the ring systems known to us — is the ideal laboratory for studying the ring phenomenon. The Voyager mission showed us how little we really know about Saturn's rings, even after four centuries of observations. While Cassini provides us with a wealth of information to help solve some of the rings' mystery, this new mission will also uncover many new clues for future investigation.

For now, scientists anxiously await the volumes of data — about those magnificent rings — that Cassini is expected to return to Earth between 2004 and 2008.

FOOTNOTES

[1] If a satellite and a ring particle have a rotational period that are integer multiples of one another, their periods are said to be in resonance.

If a ring particle orbits in exactly one-half the amount of time it takes a given satellite to complete its orbit, we have a 2:1 resonance. The ring particles in such an orbit obtain repeated gravitational "tugs," which create more collisions, which eventually thin the region of particles. The Cassini gap is the best known and best defined such zone, with the Janus 7:6 point at its exterior limit and the Mimas 2:1 point at its interior limit. In regions where the resonance effect is less pronounced, we find density waves instead of gaps in the rings.

[2] Keeler probably discovered what is known as the Encke gap, but the astronomical community has been somewhat remiss in correcting this error.

[3] Further searching in the Encke gap, where such edge waves were seen, led to the discovery of one small satellite inside the division. Called Pan, this satellite may well be responsible for clearing and maintaining the gap.

[4] The particles constituting the rings are not completely isolated from each other; they interact with one another in orbit through collisions and their mutual gravitational attraction. These interactions make the rings behave somewhat like a fluid, rather than a swarm of isolated, orbiting particles. The degree to which the particles interact is characterized as a measure of the rings' "viscosity."