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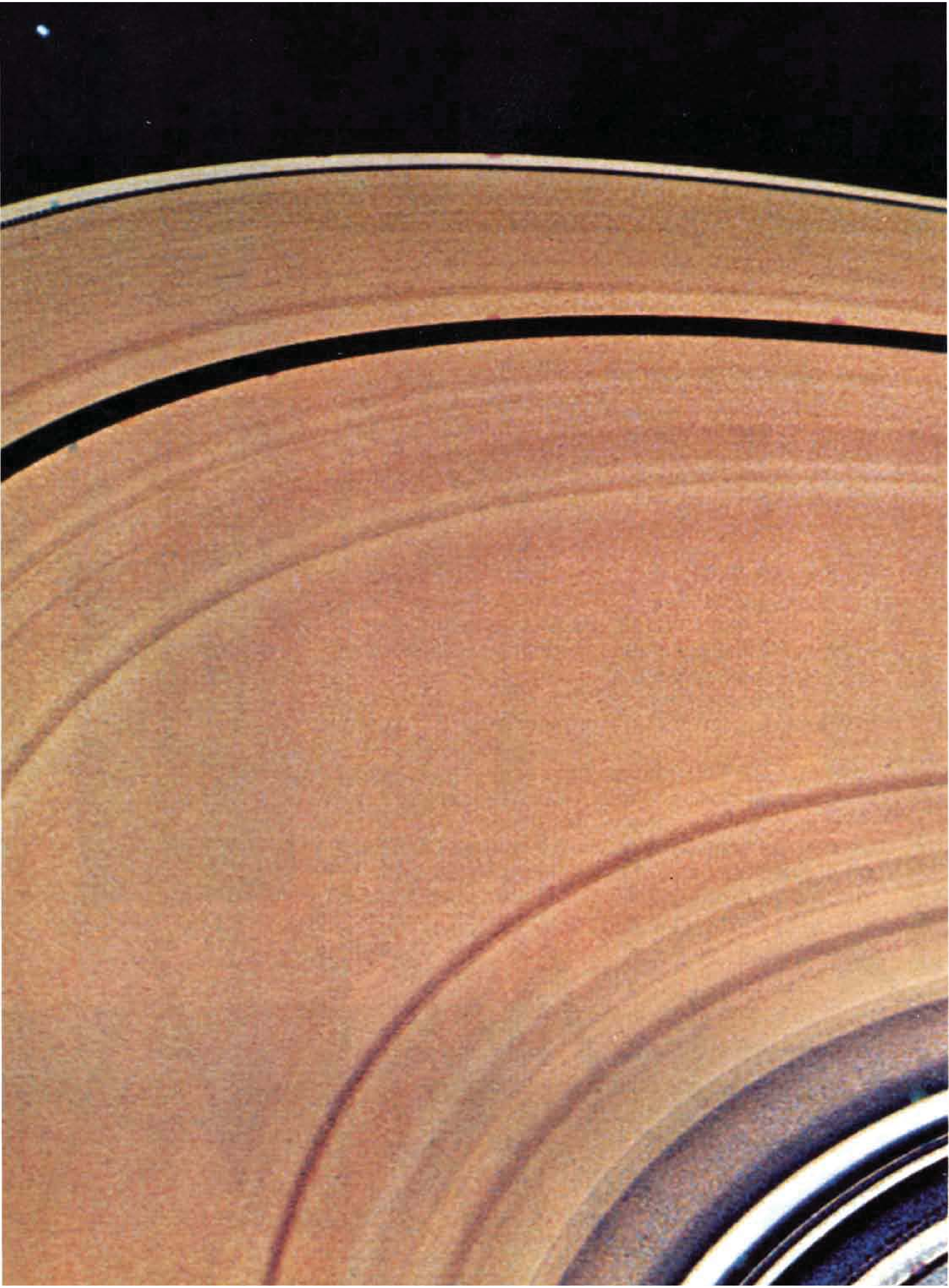


Rings in the Solar System

Three of the giant planets are now known to have them, and the rings around Saturn are now known to consist of myriad ringlets. The form of the rings is maintained by a complex interplay of sculpturing forces

by James B. Pollack and Jeffrey N. Cuzzi

The approach of the spacecraft *Voyager 2* to within 100,000 kilometers of Saturn on August 25 marks the climax of a period of planetary exploration in which the rings of Saturn have surprised us perhaps as much as they surprised the first men who saw them almost four centuries ago. Today the rings of Saturn stand revealed in a wealth of detail, including bands, spokes and braids. Some of the detail is unexplained. On the other hand, it emerges that Saturn is not unique in having rings. Jupiter has a ring, and Uranus has at least nine discrete rings. It remains to be determined whether Neptune has rings, and whether rings are therefore ubiquitous among the giant gaseous planets of the outer solar system. Here we shall discuss the structure and composition of the rings of Jupiter, Saturn and Uranus, with special attention to the rings of Saturn. Then we shall take up what is known about the processes that shape the rings. Finally, we shall consider several alternative explanations of how the rings arose.

Strange Appendages

The rings of Saturn were first observed in July, 1610. The observer was Galileo Galilei. Partly because the images produced by his invention, the astronomical telescope, were poor and partly because he had discovered the four largest moons of Jupiter only a few months earlier, he initially thought the blurry, earlike structures he saw were two moons close to Saturn. Soon his opinion changed. For one thing the "strange appendages" did not vary in their position with respect to Saturn from one night to the next. Moreover, in 1612 the appendages disappeared. Today it is plain that the rings had come to lie in an edge-on orientation as viewed from the earth in 1612 and thus had become quite faint.

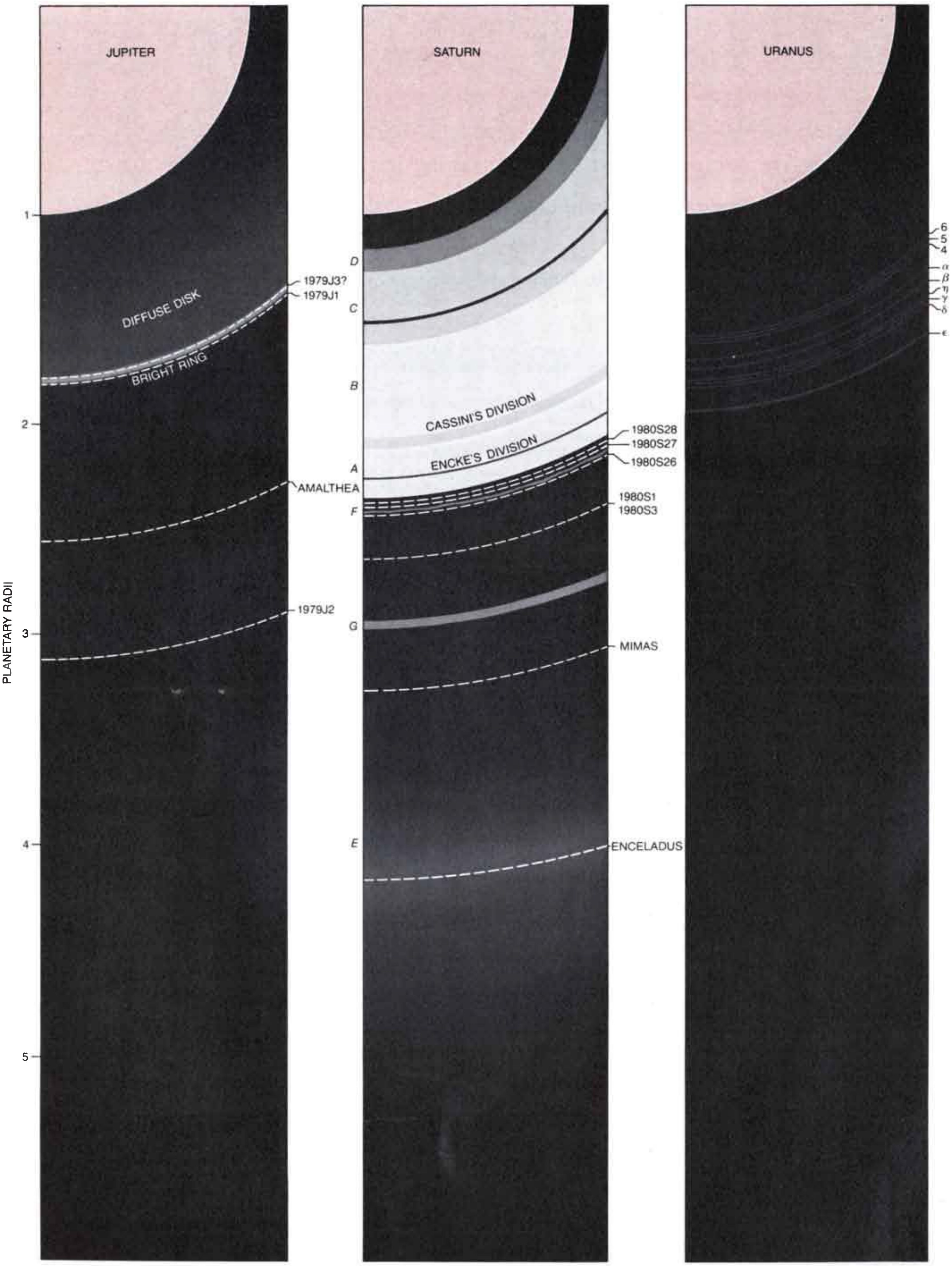
The geometry of the appendages puzzled astronomers. Indeed, it was proposed that the appendages were handles attached to Saturn or that they consisted of several moons in orbit only around the back of Saturn so that they never cast a shadow on the planet. Finally in 1655 Christiaan Huygens proposed that the appendages were the visible sign of a thin, flat, detached disk of matter arrayed in the equatorial plane of the planet. Depending on the position of Saturn and that of the earth in their orbits about the sun, the disk would vary in its tilt toward the earth; hence it would vary in appearance from a narrow line to a broad ellipse.

For the next two centuries it was assumed that the disk was a continuous sheet of matter. A difficulty with this hypothesis emerged, however, as early as 1675, when Jean Dominique Cassini found that the dark band now known as Cassini's division separates the disk into two concentric rings. Moreover, late in the 18th century Pierre Simon de Laplace showed that the combined forces of the gravity of Saturn and the rotation of the disk would rip apart a single broad sheet of matter. Basically any given parcel of the disk maintains its radial distance from Saturn because two forces are in balance. Gravity pulls the parcel inward; centrifugal force pushes it outward. The centrifugal force arises from rotational velocity; thus the disk is rotating. The problem is that for a rigidly rotating disk the forces balance at only one radial distance. Laplace therefore proposed that the rings of Saturn consist of many narrow ringlets, each one thin enough to sustain the slight imbalance of forces across its radial width.

The final step toward the modern view of the rings was taken in 1857, when James Clerk Maxwell won the Adams prize of the University of Cambridge for his mathematical demonstration that the ringlets actually consist of numerous tiny masses in independent orbits. Experimental proof for his hypothesis came from several quarters. In 1895, for example, the American astronomers James E. Keeler and William W. Campbell inferred the velocity of the particles in the rings from Doppler shifts: the altered wavelength of spectral lines in the sunlight the particles reflect toward the earth. They found that the rings rotate about Saturn at a rate different from that of the atmosphere of the planet. Moreover, the inner parts of the rings rotate at a greater velocity than the outer parts, just as the laws of physics would lead one to expect for particles in independent orbits.

The rings of Uranus were discovered by accident. A number of groups of astronomers had set out to observe the passage of the star SAO 158687 behind Uranus on March 10, 1977. The intent was to study the structure of the atmosphere of Uranus. Among the more successful observations were those made by James L. Elliot and his associates on the Kuiper Airborne Observatory, an aircraft equipped with a 91-centimeter telescope. His group (and several others) found that the brightness of the star decreased not only when it passed behind Uranus but also at a number of places close to the planet yet far above its atmosphere. The short-duration dimmings defined a series of distances on one side of Uranus that was roughly symmetrical with the series on the other side of the planet. The symmetry was taken to arise from the presence of fairly opaque, quite narrow and nearly circular rings. Later observations have revealed so far the presence of nine rings,

"A" RING OF SATURN was photographed on August 23 by the spacecraft *Voyager 2*. In the resulting image, displayed in false color, the *A* ring is yellowish; the broadest gap in the ring is Encke's division. The part of the ring outside Encke's division shows a faint set of bands. The bands are more closely spaced near the orbit of 1980S27, a moon discovered in images made by *Voyager 1* and visible as the white dot at the upper left. It is thought the bands are caused by resonances in the ring due to the gravitational effects of the moon. In addition 1980S27 and a second moon, 1980S26, are thought to shape the *F* ring of Saturn, too faint to show up here. The whitish and bluish ringlets at the lower right occupy Cassini's division. Their different colorations in this image indicate that their particles have somewhat different compositions.


JUPITER
SATURN
URANUS
PLANETARY RADII
1
2
3
4
5
DIFFUSE DISK
BRIGHT RING
1979J3?
1979J1
AMALTHEA
1979J2
D
C
B
A
F
G
E
CASSINI'S DIVISION
ENCKE'S DIVISION
1980S28
1980S27
1980S26
1980S1
1980S3
MIMAS
ENCELADUS
6
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α
β
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all lying within one planetary radius of the top of the Uranian atmosphere.

The rings of Jupiter were discovered by spacecraft. The first hint came when *Pioneer 10* passed near Jupiter in 1974. Jupiter has a magnetic field that traps charged particles in regions of space surrounding the planet. The regions amount to the Jovian equivalent of the earth's Van Allen belt. What *Pioneer 10* detected was a decrease in the count of the high-energy particles in the Jovian belts 50,000 to 55,000 kilometers above the atmosphere of the planet. Mario H. Acuña and Norman F. Ness of the Goddard Space Flight Center of the National Aeronautics and Space Administration suggested that the decrease might be due to the partial absorption of the particles by a close-in satellite or a system of rings. The latter proved to be the case. A faint Jovian ring was detected in 1979 when it was photographed by imaging systems aboard *Voyager 1* and *Voyager 2*. The spacecraft were deflected toward Saturn by the gravitational field of Jupiter. They arrived near Saturn in November, 1980, and August, 1981.

Characteristics of Planetary Rings

The rings of Saturn, Uranus and Jupiter share a number of properties. First, they consist of myriad particles in independent orbits. Second, they lie far closer to their parent planet than the major moons of the planet do; in fact, the bulk of each ring system lies less than one planetary radius away from the surface of the planet. Third, the rings are centered on the equatorial plane of the planet; indeed, almost all the ring material is confined to a thin region in that plane. Fourth, the ring systems of Jupiter and Saturn have a number of tiny moonlets near or within the rings. It is suspected that similar moonlets are associated with the rings of Uranus.

Still, each ring system has its own peculiarities. The ring system of Saturn has seven major sections. Some of them are separated from neighboring sections by more or less empty annular gaps; the borders of the others are marked by changes in the packing density of ring particles. Each section is designated by a letter that reflects not its distance from Saturn but the order in which the sections were discovered or hypothesized.

The main body of the ring system of Saturn includes, then, the bright and fairly opaque rings *A* and *B*. They are separated from each other by the 5,000-kilometer width of Cassini's division, a rather transparent region but definitely not an empty one. The main body of the Saturnian system also includes the fainter, less opaque *C* ring, which lies inside the inner edge of the *B* ring. It has a degree of opacity comparable to that of Cassini's division. The still fainter *D* ring lies inside the *C* ring. Finally, three very faint rings, *E, F* and *G,* lie outside the *A* ring. Taken together, the main rings of Saturn (the *A, B* and *C* rings) measure about 275,000 kilometers in annular width, or about three-fourths of the distance from the earth to the moon. In comparison, the thickness of the rings of Saturn is negligible. An upper limit of about a kilometer has been placed on their vertical extent. Compared with their width, the rings are thousands of times thinner than razor-thin.

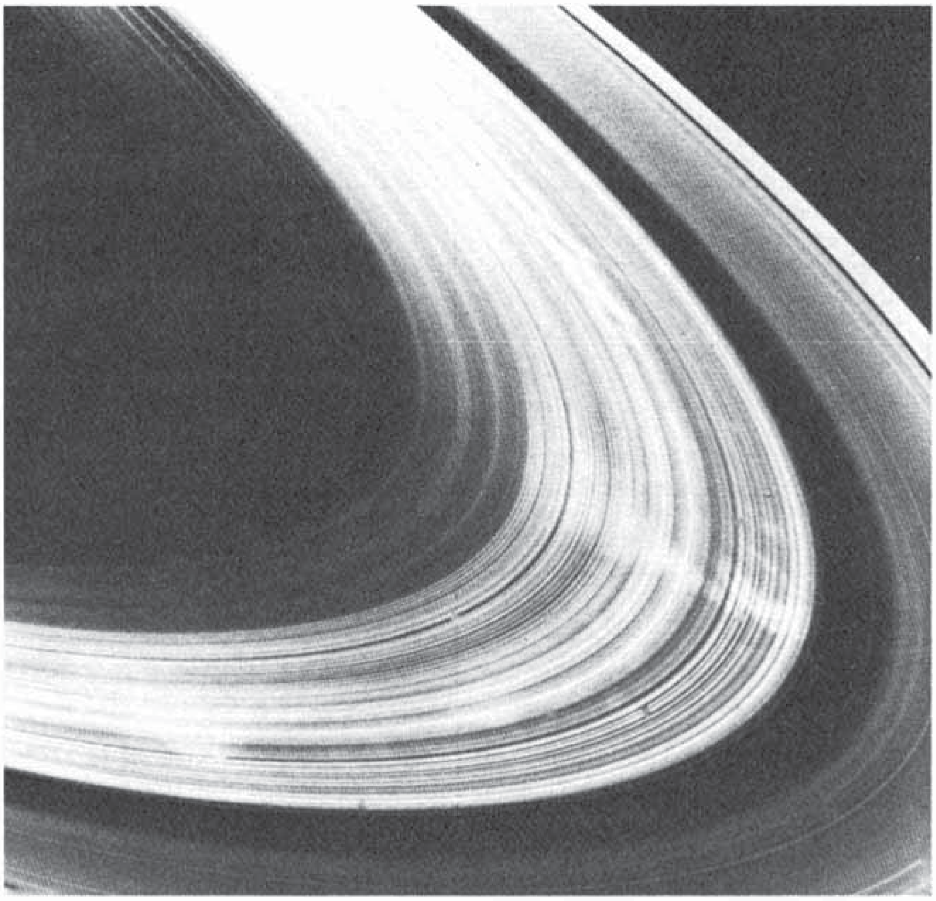
Information on the composition of the particles in the rings of Saturn can be derived from the rings' ability to reflect or absorb light of different wavelengths. For example, the *A, B* and *C* rings are poor reflectors of sunlight at certain near-infrared wavelengths. This property is characteristic of water ice, which suggests that water ice is a major constituent of the surface of the particles that make up those rings. Water ice, however, is white in color; that is, water ice is more or less equally reflective at all visible wavelengths. In contrast, the particles of the *A, B* and *C* rings are less reflective in blue light than they are in red light. Perhaps some additional substance is present in small amounts. Dust containing iron oxide has been suggested as the source of the reddish color. It has also been hypothesized that compounds generated by the sun's ultraviolet radiation are responsible for the redness. Certain colorless sulfur-containing compounds become polysulfides under ultraviolet radiation, and polysulfides selectively absorb in the blue. One surprise in the Voyager data is that the particles in the *A* and *B* rings have a similar color but are brighter and more reddish than the particles in the *C* ring and in Cassini's division.

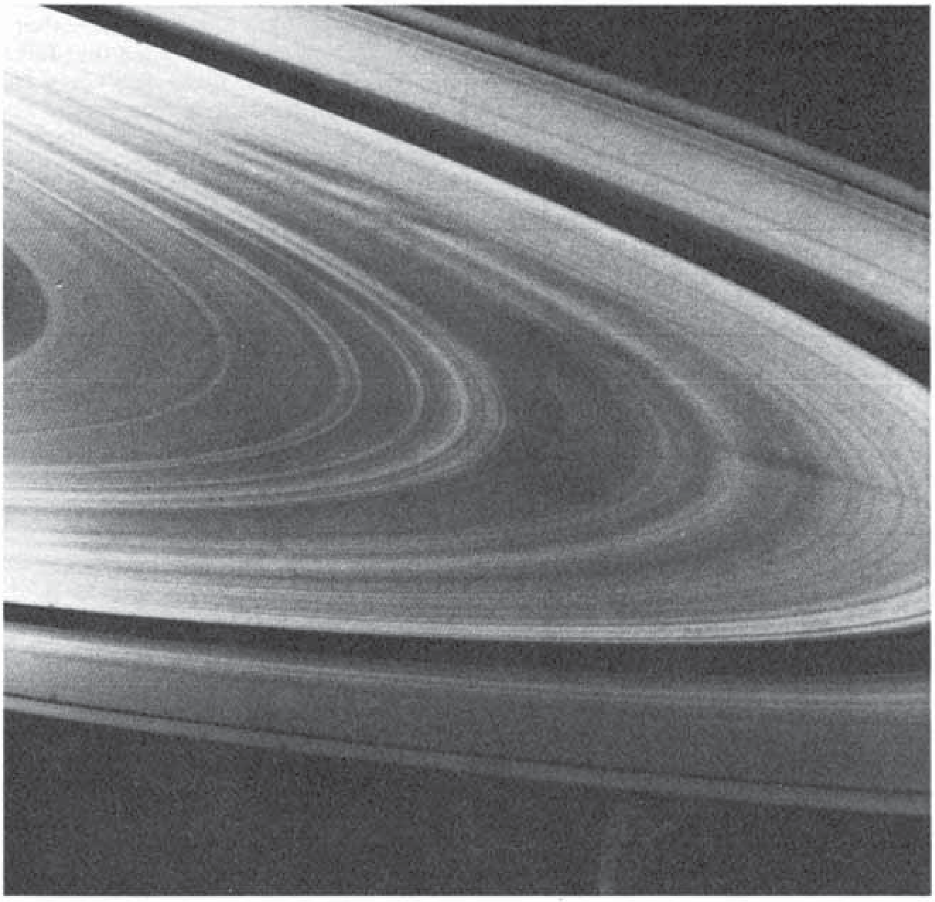
Observations with radar yield further deductions. In 1973 Richard M. Goldstein and Gregory Morris of the Jet Propulsion Laboratory of the California Institute of Technology probed the rings of Saturn with radar waves whose reflection they detected with the 210-foot antenna of the deep-space network at Goldstone, Calif. The high reflectivity of the *A* and *B* rings implied that most of the particles in those two rings are at least comparable in size to the radar wavelengths of several centimeters that the investigators employed. If they had been smaller than the radar wavelengths, they would have been transparent to the radar waves. If they had been much larger than the wavelengths, their emission of thermal radiation at those wavelengths would have been significant. The low level of such radiation limits their size to no more than a few meters.

Data from the Voyager spacecraft have supported and extended the earlier findings. In one type of experiment radio waves from the spacecraft were sent through the rings to the earth and measurements were made of the amount of power scattered by the ring particles at various angles of deflection from the initial path of the waves. As the size of the particles increases with respect to the wavelength, the scattering pattern becomes more narrowly concentrated within small angles of forward deflection. An analysis of the Voyager data by G. Leonard Tyler and Ahmed Essam A. Marouf of Stanford University indicates that the largest abundant particles in the *A, B* and *C* rings are about 10 meters in size. More abundant particles are as small as 10 centimeters, and regional variations in the distribution of sizes are found among the rings.

Just as the scattering of radar waves by the particles in the rings makes it pos-

RING SYSTEMS around Jupiter, Saturn and Uranus are diagrammed at scales on which the radius of each planet is set equal to 1. Jupiter (*left*) has a "bright" ring that is actually quite faint and almost transparent. An even fainter disk of particles extends inward from the ring, perhaps into the atmosphere of the planet. A halo of particles (not shown) gives the system a vertical thickness of some 20,000 kilometers. The system was discovered by spacecraft. Saturn (*center*) has seven rings. The *A* and *B* rings are separated by Cassini's division; the *A* ring includes Encke's division. Letters were assigned to the rings in the order of their discovery. Only the main rings (the *A, B* and *C* rings) are readily visible in earth-based telescopes; the rest (except the *E* ring) were discovered by spacecraft. Uranus (*right*) has no fewer than nine rings. Here their width is exaggerated. They were detected from the earth, and they are designated by numbers or Greek letters. The moons in the ring systems are labeled at the right of each panel; their orbits are in broken lines. The relative sizes of Jupiter, Saturn and Uranus are shown above.





SPOKES AND BANDS in the rings of Saturn were first photographed by *Voyager 1.* The spokes arise sporadically in the *B* ring; they are more or less radial wedges. Each spoke is bright in images of the sunlit face of the rings made when the spacecraft and the sun are on opposite sides of Saturn, so that sunlight reflects forward from the ring particles to the spacecraft (*top photograph*), and each spoke is dark in images made when the spacecraft and the sun are on the same side of Saturn, so that sunlight reflects backward (*bottom photograph*). In both images the banding of the rings into ringlets is evident. The wide dark band is Cassini's division.

sible to detect particles on the order of the size of a radar wavelength, so the scattering of sunlight makes it possible to detect particles the size of a wavelength of visible light. In particular, the strong brightening of a segment of ring when it is viewed at small forward scattering angles implies that particles on the order of a micrometer in size are abundant in the segment. Such an observation can be made only when Saturn comes between the sun and the observer. For observations from the earth this condition cannot be met, but for observations from spacecraft it can be. Thus studies of the Voyager data indicate that particles on the order of a micrometer in size constitute a large fraction of the particles in the *F* ring, a significant fraction in many parts of the *B* ring and a less significant fraction in the outer part of the *A* ring. On the other hand, the *C* ring and Cassini's division show no sign of such small particles.

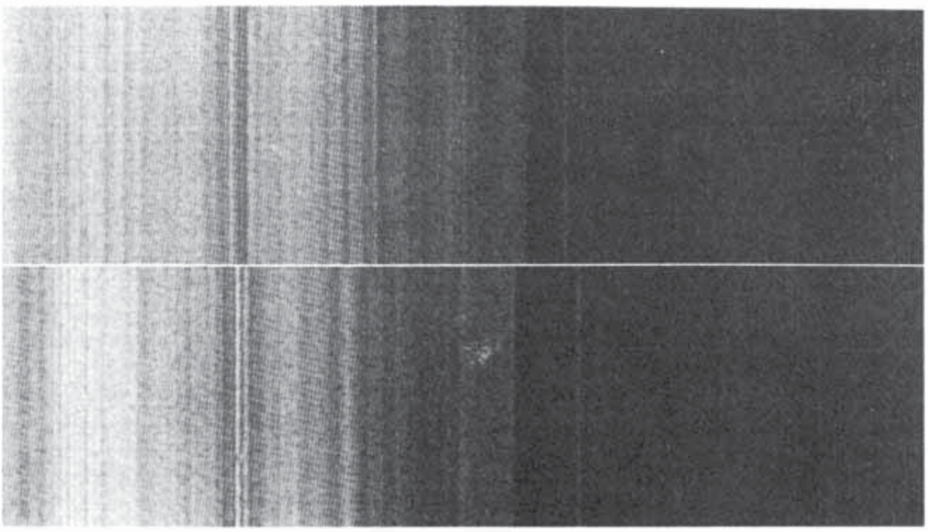
Structure in Saturn's Rings

Before the passage of the Voyager spacecraft near Saturn a limited amount of structure was recognized in the planet's rings. Cassini's division was of course known, and so was Encke's division, a narrower band in the outer part of the *A* ring. The high-resolution photographs of the rings made by the Voyager spacecraft revealed a number of surprises. Narrow annular regions of differing brightness and opacity appeared, seemingly as numerous as the grooves on a phonograph record. In addition deviations from circularity were found. These include radially oriented, wedge-shaped spokes in the *B* ring and knots, braids and twists in the *F* ring.

The greatest amount of detailed structure is exhibited by the *B* ring, which also has the greatest density of particles found anywhere in the rings. Variations in the opacity of the *B* ring occur over radial distances as small as 10 to 50 kilometers. In contrast, the *B* ring has an overall width of 25,000 kilometers. The central, most opaque part of the *B* ring is where the spokes appear. Typically each spoke can be seen for a significant part of the 10 hours it takes a parcel of the *B* ring to complete one orbital revolution. Meanwhile new spokes are arising sporadically in new locations in the ring. Compared with their surroundings the spokes appear bright in forward-scattered light and dark in backscattered light. Hence particles on the order of a micrometer in size are particularly abundant in the spokes.

Each part of a spoke orbits Saturn at the same velocity as that of the ring particles at its radial distance. The inner sections move faster; thus a spoke becomes more tilted with time. Eventually it disappears. The narrow end of each wedge-shaped spoke seems to coincide approximately with the distance from of about 6,000 kilometers. Its fairly sharp outer boundary lies about 58,000 kilometers, or .8 Jovian radius, above the surface of Jupiter. In the outer part of the ring a narrow band some 600 kilometers wide is about 10 percent brighter than the rest. Still, the opacity of the "bright" ring is so low that only .001 percent of the sunlight passing through it is intercepted by its particles. The diffuse disk is several times fainter. It extends inward from the inner margin of the bright ring. Indeed, it may intersect the atmosphere of Jupiter. Viewed edge on, the bright ring and the disk appear to be confined primarily to a thickness of no more than 30 kilometers. Remarkably, however, the halo has a vertical extent of some 20,000 kilometers. The halo is highest over the diffuse disk. Its outer boundary extends a little beyond the outer edge of the bright ring.

On the basis of the way the bright ring brightens at small scattering angles it has been found to contain particles whose characteristic size is several micrometers. Such particles are quite ineffective at absorbing high-energy protons and electrons. Hence these particles cannot be responsible for the decrease in the flux of high-energy particles detected in the bright ring by the *Pioneer 10* spacecraft. There must also be particles at least a centimeter in diameter. The particles in the ring are reddish, which makes them the color of many asteroids and moons of the outer solar system.



DISTORTIONS IN THE RINGS of Saturn are evident in a comparison of images made on opposite sides of the rings by *Voyager 2*. In each image the *B* ring is the bright region at the left; Cassini's division is the dark region at the right. The outer edge of the *B* ring is shown to be noncircular, and the presence of a bright eccentric ringlet outside the edge of the *B* ring is confirmed. (The ringlet was discovered by *Voyager 1*.) Particles near the outer edge of the *B* ring orbit Saturn twice for each single orbit of the moon Mimas. This resonance greatly amplifies the gravitational effect of Mimas and thereby distorts the *B* ring; overall the resonance raises bulges on opposite sides of the ring. In contrast, the eccentric ringlet has a single maximum that may result from the gravitational field of a local moonlet that has not yet been detected.

Collisions in the Rings

The architecture of a ring system results from the interplay of a number of forces. These include gravitational forces due to moons outside the rings and the moonlets embedded in them, electromagnetic forces due to the planet's rotating magnetic field and even the gentle forces exerted by the dilute gaseous medium in which the rings rotate.

All the particles in a ring system share a common orbital motion around a planet: they travel in the direction of the planet's rotation. The vertical and radial motions superimposed on the orbital motion of each such particle have no similar constraint. Hence neighboring particles move randomly in these directions with respect to one another, and collisions are inevitable. When the random relative velocities are large, as they might have been if the rings were ever a thick cloud of particles, the collisions are violent, and even if the collisions are rare, a great amount of the energy of relative motion goes into heating the particles and deforming their structure. The consequent loss of energy means that the random velocities rapidly decrease. The decrease in the vertical component of the velocities leads to a flattening of the ring system. Meanwhile the decrease in the radial component leads to more nearly circular orbits. In brief, a fat ring becomes a thin and roughly circular disk quite early in its history.

Even when the ring particles have lost almost all their random motion, the collisions continue. The reason is as follows. The force of gravity exerted by the planet on the particles in a ring weakens with increasing distance from the planet, so that ring particles at greater distances take longer to circle the planet. Thus a ring particle whose orbit is slightly inside that of a second ring particle eventually catches up with it, and the two of them collide if their radial separation is less than the diameter of a particle.

The collision is likely to happen at a relative velocity of less than a centimeter per second. Nevertheless, it can convert a little of the particles' circular orbital motion into random vertical motion. Subsequent collisions will prevent the particles' vertical velocities from becoming very great. A steady state will therefore be reached that determines the thickness of the ring. If the particles have a wide range of sizes, the smaller particles will gain vertical velocity mostly by being gravitationally deflected in near-miss encounters with the bigger particles. They will lose their vertical velocity mostly by colliding with other small particles. Under these circumstances the small particles will attain a vertical extent several times the size of the biggest abundant particles. In the case of the *A* and *B* rings of Saturn the small particles would be expected to occupy a vertical thickness of 10 to 100 meters. Measurements made by experiments on the Voyager spacecraft indicate that the main rings of Saturn are certainly no more than a few hundred meters thick. The range of the measurements makes the observational thickness compatible with the predicted thickness.

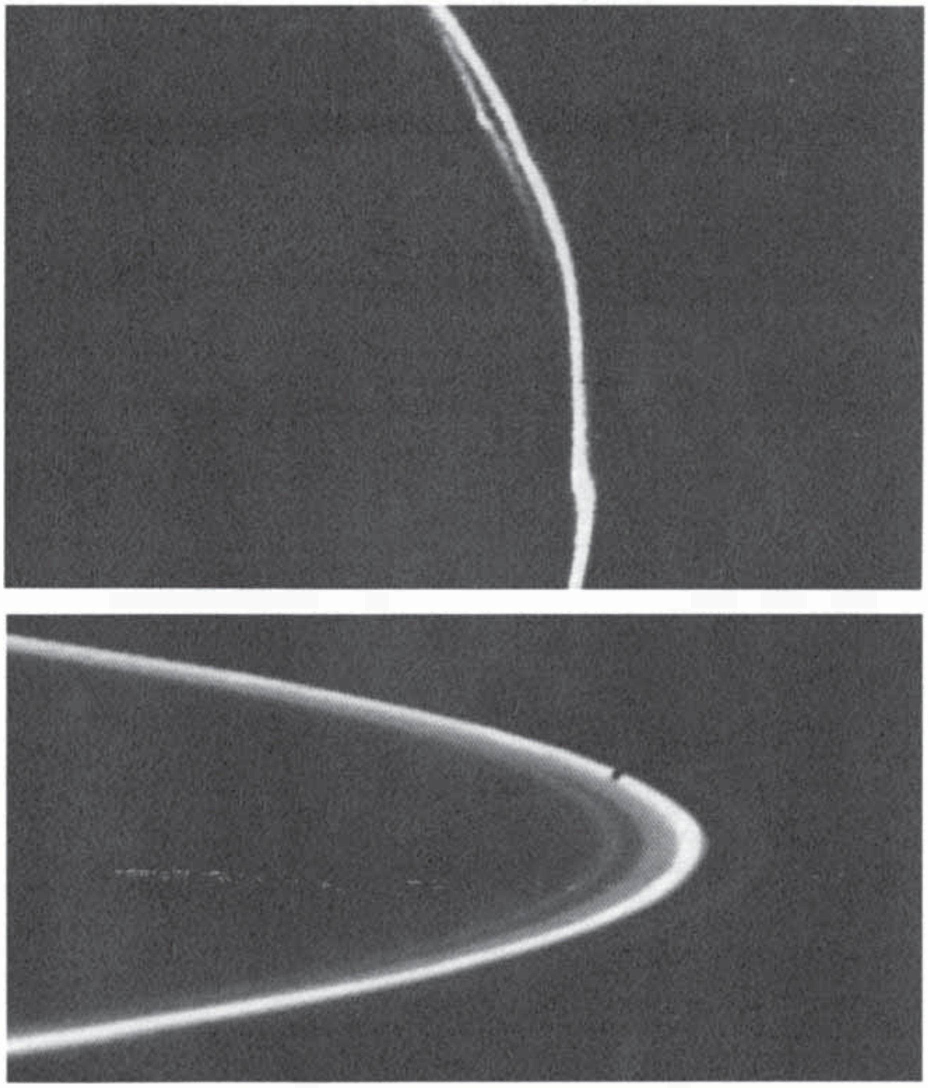
The collisions of neighboring particles will also convert some of their circular orbital motion into radial motion. Hence the rings will spread radially. An isolated, unconstrained ring will spread until its particles are far enough apart for their collisions to virtually cease. The bright ring of Jupiter may have attained this end state. The width and the very low opacity of the bright ring may reflect the collisionally induced spreading of its larger particles over the age of the solar system.

The rings of Saturn and Uranus, however, display abrupt, well-defined boundaries that limit regions densely filled with particles. Other processes must therefore be counteracting the rapid spreading induced by frequent collisions. An important role in these processes may be played by moonlets embedded in the rings or adjacent to them. The gravitational fields of larger, more distant moons may serve to lock some of the local moonlets into fixed orbits and in that way prevent the moonlets from being dislocated by their gravitational interactions with the ring particles around them.

Fundamentally the motion of bodies in orbit around a much more massive planet is dominated by the planet's gravitational field. In certain instances, however, the gravitational attraction between two relatively tiny orbiting bodies may be amplified and thus may come to affect their motion significantly. Such amplification is known as resonant forcing or simply as a resonance. Consider that if the orbital period of a moon is an exact multiple or fraction of that of another moon, the net gravitational effect of each moon on the other is in essence a push or a pull applied repeatedly at the same point in the cyclical motion. Thus the effect is amplified. In some instances resonant forcing locks pairs of moons into orbits whose periods maintain a fixed ratio of two small integers. Such commensurabilities are well known in the Jovian and Saturnian satellite systems, where they involve at least four pairs of the major moons and probably several of the newly discovered moons as well.

Resonance and the Rings

A rather different situation applies to a resonance in a disk of particles. Close to the radial distance from the planet at which the particles in the disk would have an orbital period commensurate with that of one of the planet's moons, the amplification of the gravitational effect of the moon over long periods of time causes the orbits of the particles to become noncircular. Thus the particles are made likely to collide with their less perturbed neighbors. As a result the particles are lost from a band at the radial distance of a resonance. Typically the band has a natural width of some tens of kilometers. Examples of such bands in the rings of Saturn probably include the dozens of narrow gaps in the outer part of the *A* ring, which seem to have resulted from resonances caused by the newly discovered moons designated 1980S1, 1980S3, 1980S26 and 1980S27. The predominance of small particles near the gaps probably attests to the violent collisions induced locally by each resonance.



BRAIDS IN THE "F" RING of Saturn were revealed in photographs made by the *Voyager 1* spacecraft when it passed near the planet in November, 1980, but when *Voyager 2* arrived nine months later, they were gone. The ring itself is some 80,000 kilometers (1.3 Saturnian radii) from the surface of Saturn and 4,000 kilometers from the outer edge of the *A* ring. In November, 1980 (*top*), it consisted of three strands, each some 30 kilometers wide. The outer two strands exhibited kinks, warps and knots, and they seemed to be braided, or at least to intersect. The gravitational fields of the moons designated 1980S26 and 1980S27 may account for such structural distortion. By August, 1981 (*bottom*), the *F* ring had changed its structure substantially. An unbraided strand was dominant; three fainter strands appeared as companions.

One additional effect of the resonances that are distant from a moonlet should also be mentioned here. In 1978 Peter M. Goldreich of Cal Tech and Scott D. Tremaine, now at the Institute for Advanced Study in Princeton, proposed that spiral waves of fluctuation in the density of the ring material are present in the rings of Saturn. It had been suggested earlier that similar waves are responsible for the spiral-arm pattern of galaxies such as the Milky Way. In images made by *Voyager 1* spiral density waves seem to be faintly visible in Cassini's division; their tightly wound pattern is reminiscent of a watch spring. It is thought the waves are raised there by resonances. The waves may convey the effects of the resonances over great distances; hence the waves may turn out to play a central role in transporting material within the disk formed by Saturn's rings.

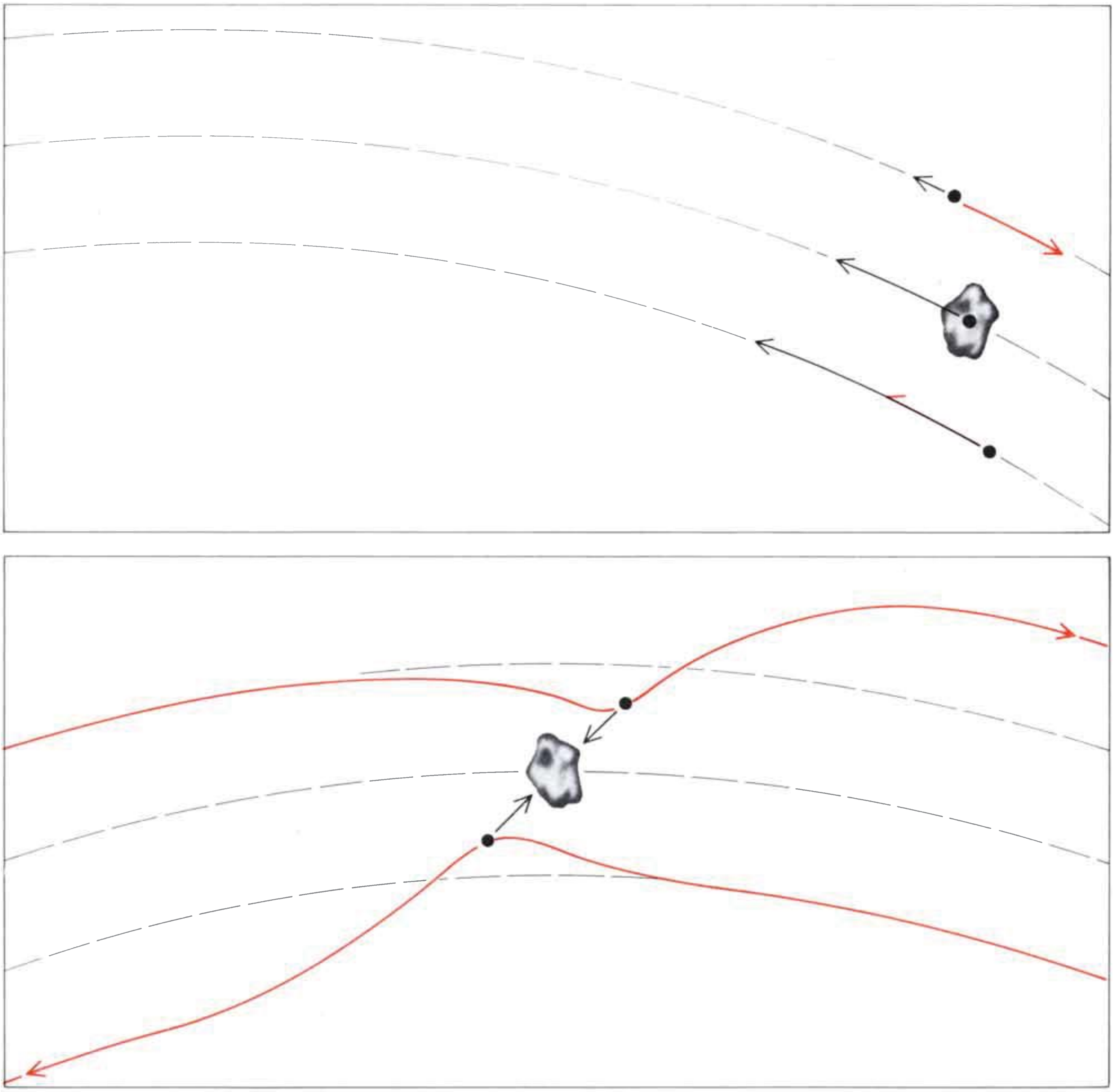
The resonances created in a disk by a moon are spaced closer together as the orbit of the moon is approached. At some critical distance the radial spacing between successive resonances becomes equal to the natural width of each resonance. Within this critical distance the resonances overlap. The result is a continuous zone of transfer of ring material that clears the ring material away from the orbit of the moon. The width of the zone and the degree of clearing in it will depend on the mass of the moon and the density of the surrounding ring material. The more massive the moon, the wider the zone, but the denser the packing of ring particles, the more often it will happen that collisions between particles will propel some of the particles back into the zone. Jack Lissauer and Frank H. Shu of the University of California at Berkeley and M. Hénon of the Nice Observatory have shown that if moonlets from several kilometers to tens of kilometers in size were embedded in the rings of Saturn, the moonlets could cause much of the fine structure in the rings. As of this writing, however, no moonlets have been detected in even the most likely locations in the images made by *Voyager 1* and *Voyager 2*.

If the moon is adjacent to a ring, still another effect is possible: the overlapping resonances that surround the orbit of the moon can prevent the ring from spreading and give the ring a sharp boundary. The outer edge of Saturn's *A* ring is probably maintained in this way by the moons 1980S26 and 1980S27. The ring in turn repels the moons. As it happens 1980S26 is quite close to a radial distance from Saturn that would trap it in a resonance with the much more massive moon Mimas or Tethys. Such a resonance would "anchor" its radial distance, so that it could continue to sculpture the outer edge of the *A* ring. The only trouble with this hypothesis is that precise measurements seem to place

1980S26 slightly away from the anchoring distance.

Finally, two moons whose orbits are close together can prevent a narrow ring between their orbits from spreading radially. For example, 1980S26 and 1980S27, whose orbits are separated radially by only some 2,000 kilometers, may act as shepherds to confine the narrow, multistrand *F* ring between them. When one or both of the moons pass close to a given strand of the ring, their gravitational tug may generate distortions such as the ones seen in the images of the ring made by *Voyager 1*. Still, it is not clear why the *F* ring should consist of multiple narrow strands rather than a single somewhat broader strand, and why one of the strands recorded by *Voyager 1* was untwisted. In images made by *Voyager 2* the *F* ring exhibits no braids or other distortions, and the number of strands seems to have changed.

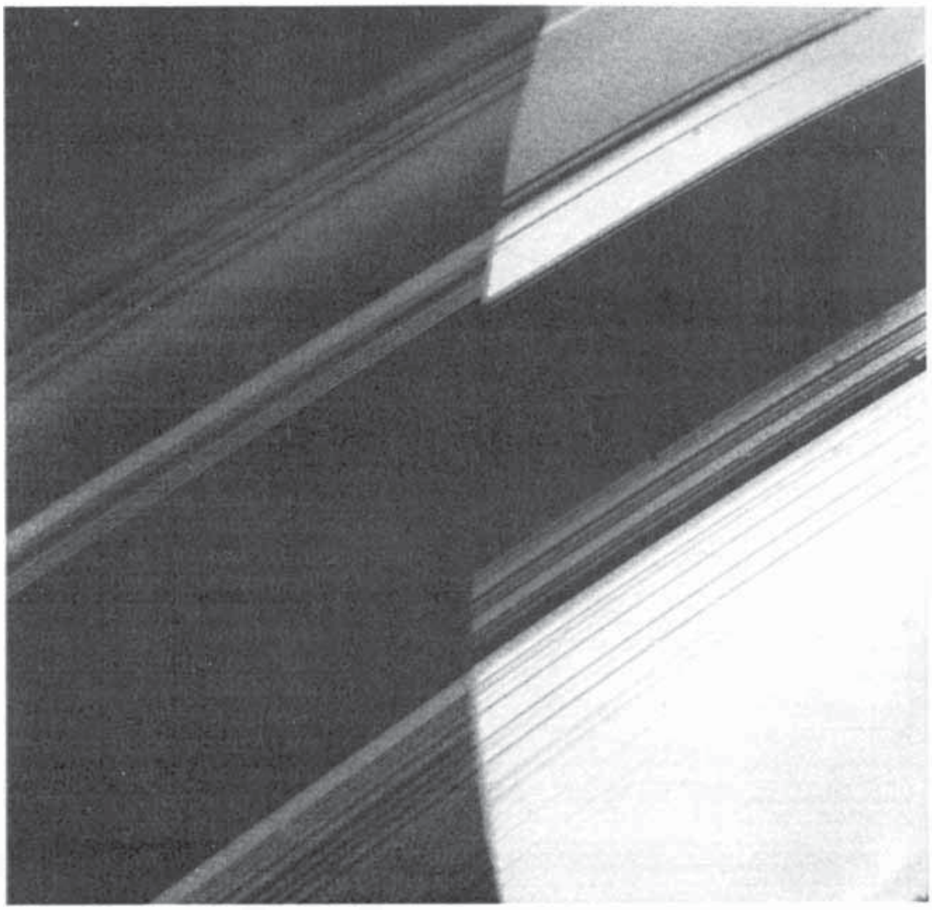
Whether shepherding moonlets produce smooth ringlets (such as the narrow, eccentric ringlets in Saturn's *C* ring and Cassini's division and probably the ϵ ring of Uranus) or kinky ringlets (such as those of Saturn's *F* ring and the ones in Encke's division that were found to be kinky in images made by *Voyager 2*) may depend on the ringlets' degree of opacity, or equivalently their particle density. In a ringlet that is rather transparent collisions between particles are relatively infrequent; hence the "echoes" of past



GRAVITATIONAL SHEPHERDING of particles by moonlets in the midst of a ring system may account for some of the banding in the rings of Saturn. The top drawing shows a moonlet and two representative particles in orbit around a planet. In accord with physical law the inner particle moves faster than the moonlet, which in turn moves faster than the outer particle (*black arrows*). Thus the moonlet is being overtaken by the inner particle at the same time as it in turn overtakes the outer particle (*colored arrows*). Each particle is drawn toward the moonlet by gravitational attraction; hence each particle is closer to the moonlet just after they are neck and neck in their orbits around the planet than it was just before. The bottom drawing shows the result. The net gravitational tug the moonlet exerts on the outer particle is in the direction of the outer particle's orbital motion, and so the outer particle is raised to a higher orbit. Conversely, the tug the moonlet exerts on the inner particle is opposite to the direction of orbital motion; the inner particle falls into a lower orbit. Ultimately the moonlet clears out a band surrounding its trajectory. The more massive the moonlet is, the wider the band will be.

gravitational perturbations may persist. In a ringlet that is more nearly opaque the greater incidence of collisions may damp the perturbations.

A full understanding of the physics of the interactions of rings with moonlets is not yet at hand. For example, Stanley F. Dermott and Thomas Gold of Cornell University have offered a hypothesis in which a narrow, eccentric ringlet with sharp edges is maintained by a single small moonlet hidden inside it rather than by a pair of surrounding moons or moonlets. Moreover, the lack of success (so far) at finding moonlets embedded in the main rings of Saturn means that other explanations of the fine radial structure in places such as the *B* ring must be explored. One hypothesis proposes that ring particles may respond to transient increases or decreases in their packing density by a further increase or decrease. Suppose the density of particles increases locally. The collisions between the particles become more numerous, and since some of the energy of the collisions is lost in the heating and deforming of the particles, their energy of random motion decreases. Unless the further collisions at lower velocities lose a smaller proportion of their energy the process of collision and coalescence continues. It is proposed that the overall result might be radial variations in the opacity of a ring.



VARIOUS DEGREES OF TRANSPARENCY and thus of the packing density of particles in the rings of Saturn are evident in an image made by *Voyager 1* that shows the unlit face of the rings as they cross the bright disk of the planet. The disk shines through most of the *C* ring (*bottom*), and it shines through Cassini's division to a similar extent, although both include ringlets whose opacity is greater. In contrast, much of the *B* ring (*middle*) is almost opaque.

Other Forces in the Rings

Small particles in the rings can be affected by forces other than gravity. Electromagnetic forces are an important example. The rings of Jupiter, of Saturn and possibly of Uranus lie in the midst of a plasma of low density, that is, they lie in a tenuous gas consisting of negatively charged electrons and positively charged ions. The electrons are less massive than the ions; therefore they move faster, and initially they collide with particles in the ring more often than the ions do. Eventually the particles become negatively charged by their absorption of electrons. At that point their charge repels the arrival of further negatively charged particles. More important, the ring particles themselves are now accelerated by an electromagnetic force as they cross the planet's magnetic field. If the particles are smaller than about .1 micrometer, the electromagnetic force is greater than the planet's gravitational attraction, and so it dominates their motion.

Several aspects of the structure of ring systems might thereby be explained. With Jupiter, for example, the axis of the magnetic field is tilted by some 10 degrees with respect to the axis of the planet's rotation. In such circumstances electromagnetic forces can give small particles a vertical distribution much greater than that of larger particles. The vertical extent of the halo of Jupiter's ring system is comparable to the extent that would be expected for particles whose size is .1 micrometer or smaller. With Saturn electromagnetic forces may turn out to be important for the peculiar structure of the *F* ring. Moreover, a number of ingenious theories have been advanced to explain how the spokes in Saturn's *B* ring arise without a simultaneous disturbance of the finely banded radial structure of the ring. Some of these theories invoke a rain of charged particles from either the planet or the rings themselves as a way of transferring electric charge to micrometer-size particles and lifting them from the surface of larger particles. The lifted particles are recaptured when they later collide with other large particles.

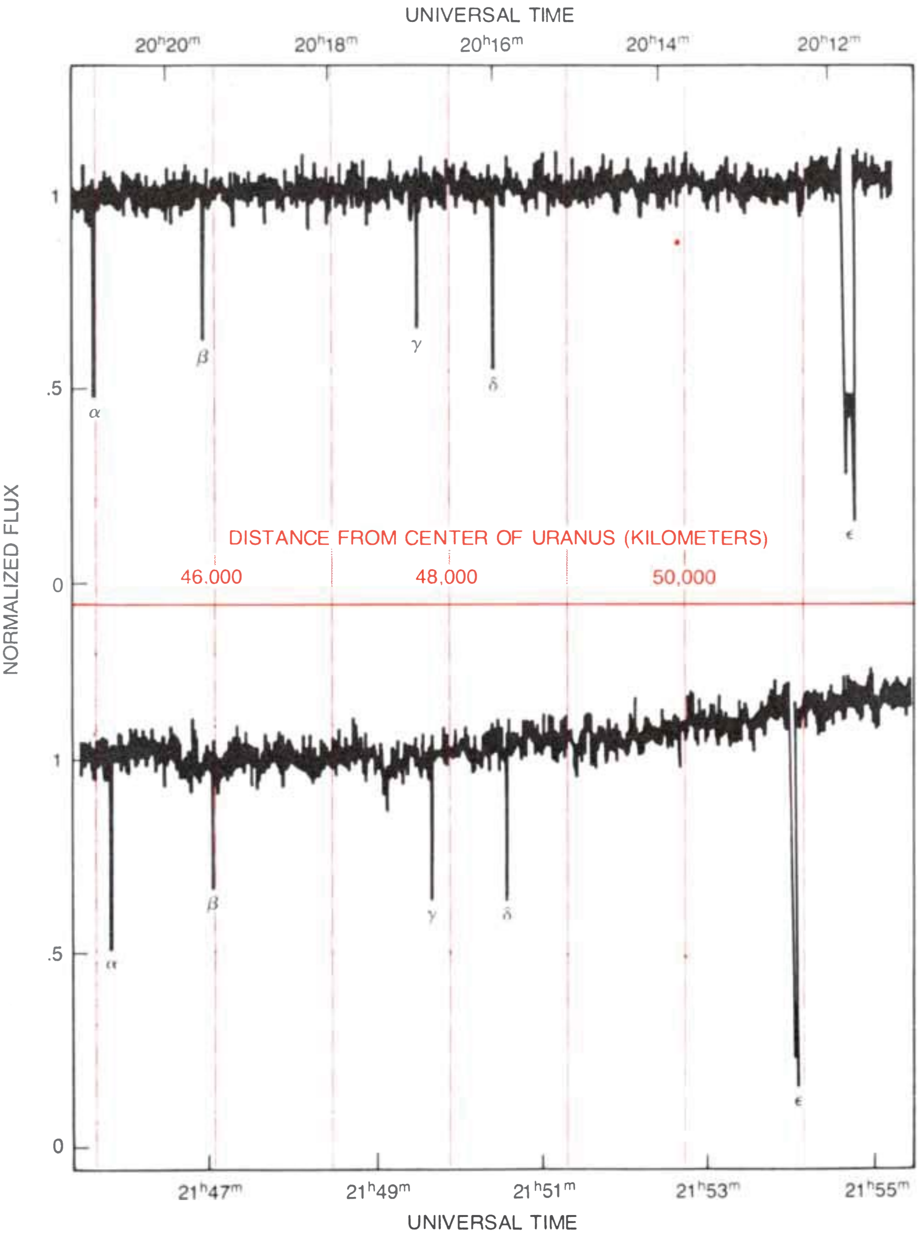
A second force that may dominate the motion of small particles in the rings is gaseous drag. Here the friction due to the presence of the plasma causes ring particles to spiral toward the planet. The smaller the particle, the faster the decay of its orbit. In only some 20 years, for example, gaseous drag can cause a micrometer-size particle to move from the outer edge of the bright ring of Jupiter to the inner edge. Another 200 years would take it through the diffuse disk and into the planet's atmosphere. The relatively structureless appearance of Jupiter's bright ring may arise in part from this rapid radial motion of the small particles in it. Indeed, the diffuse disk may be populated by particles that move into it from the bright ring.

In addition to gravity, electromagnetic forces and gaseous-drag forces, the small particles in a ring system are subjected to collisions that destroy them. For one thing interplanetary space contains solid bodies whose size ranges from less than a micrometer to more than a kilometer. The smaller bodies are by far the most numerous. The interplanetary bodies are in orbit around the sun, whereas the ring material is in orbit around a planet. Hence the two can collide at velocities of several tens of kilometers per second. If the interplanetary body is larger than about a hundredth the size of the ring particle, the collision destroys the particle. On that basis it can be estimated that a micrometer-size particle in any of the ring systems lasts for only about 10,000 years. Another type of collision may be even more destructive. In Jupiter's ring and in the outer rings of Saturn it is likely that a particle smaller than 10 micrometers is eroded by its collisions with high-energy ions in the planet's Van Allen belt well before a micrometeoroid hits it.

How did the rings arise? The sun, the

planets, the moons, the asteroids and the comets of the solar system are all thought to have formed about 4.6 billion years ago inside the solar nebula, a diffuse cloud of gas and dust. The sun and the giant planets Jupiter, Saturn, Uranus and Neptune formed in large part (or even entirely) from the gases of the nebula; Mercury, Venus, the earth, Mars, Pluto, the moons, the asteroids and the comets formed from solidified matter. The composition of the solidified matter would have depended on the temperature of the nebula from place to place. In general, however, the solidified matter consisted of varying mixtures of "rock" (which included silicates and iron) and "ices" (which included water).

At first Jupiter and Saturn, and perhaps Uranus and Neptune, were several hundred times larger than their current dimensions. Under the influence of their own gravitation they gradually shrank. As they did so they rotated faster. Eventually the increasing centrifugal force associated with the rotation caused the outermost part of each incipient giant planet—in essence a gaseous envelope—to become distinct from the more nearly spherical concentration of gas inside it, which continued to contract. The envelope served as a source of the solid grains from which the large moons of the planet accreted. Some of the grains would have formed from the condensation of gases such as water vapor as the envelope cooled. Perhaps the same process of accretion of grains into larger objects gave rise to a ring



URANUS' RINGS WERE INFERRED from the series of dimmings recorded as a star passed behind Uranus in 1977. The pattern of dimmings minutes before the star disappeared behind the planet (*top*) matched the pattern minutes after it reemerged (*bottom*). For four of the dimmings the match was almost exact; thus four rings are nearly circular. A fifth ring, designated epsilon, is notably eccentric. Further observations have shown four more rings. The data were collected by James L. Elliot and his colleagues on the Kuiper Airborne Observatory.

system somewhat closer to the planet.

After an interval on the order of a million years the circumplanetary envelopes disappeared. Perhaps they were blown away by a wind of ionized gas from the youthful sun, or perhaps friction within the envelopes caused them to collapse onto their planets. In any case the formation of moons, moonlets and ring particles ended.

Circumplanetary Conditions

Today Jupiter and Saturn give off about twice as much energy to space in the form of infrared radiation as the amount of energy they absorb in the form of sunlight. The excess represents the conversion of gravitational energy into heat by each planet's past and present contraction. At the time their moons were forming the planets were contracting much more rapidly. Hence Jupiter and Saturn and perhaps the other giant planets may have radiated many thousands of times more heat then than they do now. This heat may well have controlled the temperature and thus the composition of the solid matter in the circumplanetary envelopes. At a given time the temperature would have increased toward the planet and at a given place the envelope would have steadily cooled with time.

Several hypotheses about the origin of the ring systems around three of the giant gaseous planets posit that ring material formed in the circumplanetary envelopes at positions close to its current radial distances. Variations in temperature and other conditions near each planet may thus have been the cause of striking differences in the composition of their close-in moons and their ring material. The mean densities of the four largest moons of Jupiter imply that the inner two consist almost exclusively of rock and the outer two of comparable amounts of ice and rock. Since Jupiter's ring is well inside the orbit of the innermost large moon, any particles that formed near the ring could have consisted only of rock. Indeed, they could have consisted only of the relatively rare minerals that condense at high temperatures.

In contrast, the innermost large moons of Saturn all consist substantially of ice. Thus the temperatures even at the small distance from Saturn where the planet's rings now lie may have been cool enough to allow the formation of particles made up in large measure of water ice. The differences between the conditions around Jupiter and those around Saturn are readily explained. First of all, the amount of heat generated in early times by the contraction of a gaseous sphere depends approximately on the square of its mass. Jupiter, with more than three times the mass of Saturn, emitted 10 times more heat. It may also be that not much rock was available near Saturn for incorporation into particles. When Saturn's circumplanetary envelope formed, the planet's atmosphere probably extended into the region now occupied by the rings and the innermost moons. Hence most of the rocky grains there may have been kept in Saturn's atmosphere. They may also have been claimed by the moons farther out.

The hypotheses that the temperature near Saturn was relatively low and that little rock was available there are consistent with the finding that the inner moons of Saturn have a lower mean density and consequently a larger fractional content of ice than most of the outer moons. The hypotheses may also help to explain why Saturn's rings seem to be almost pure water ice, whereas Jupiter's are rock. Yet it seems the rings of Uranus are rock. One would think they would have been ice.

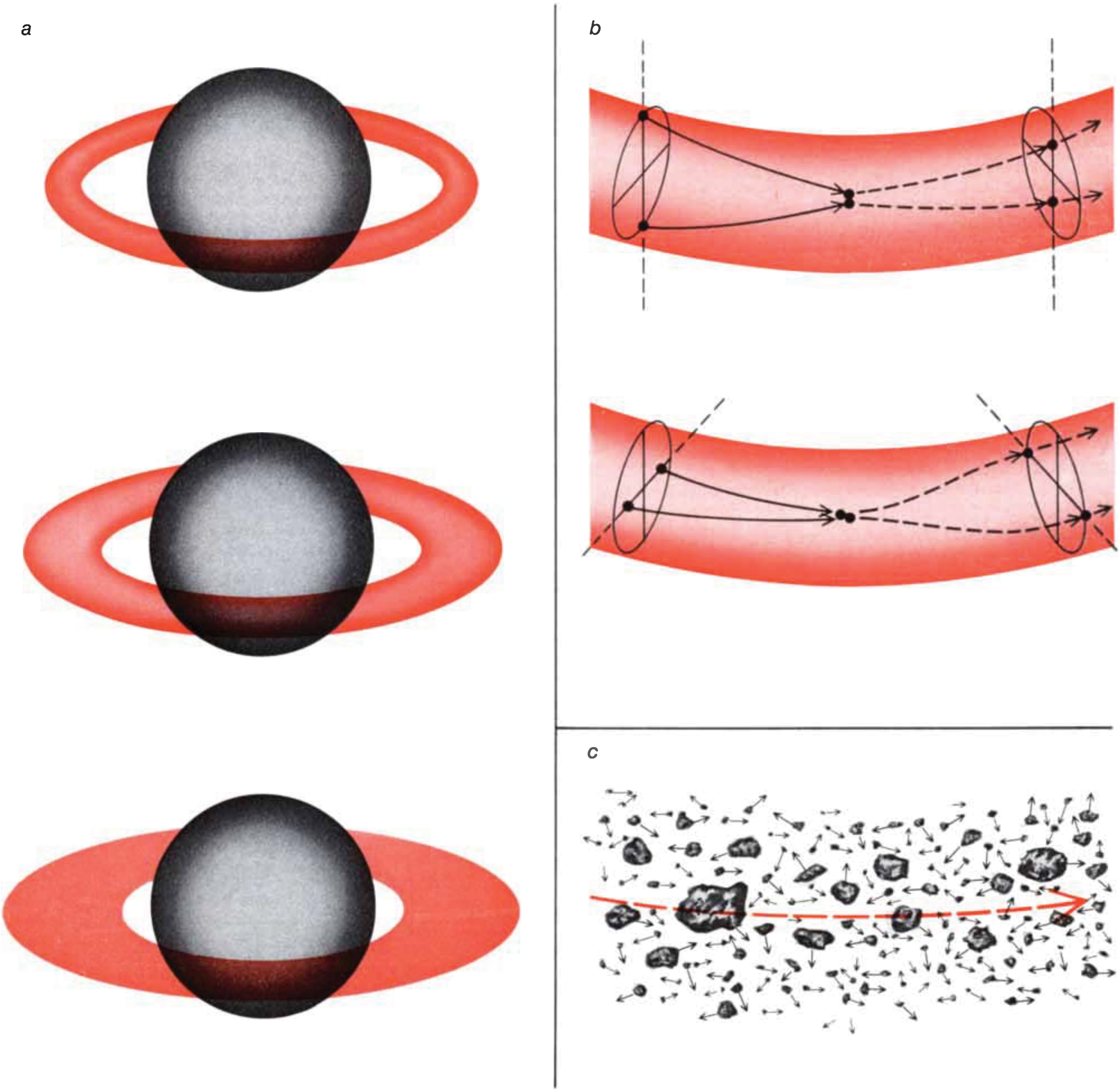
Rival Hypotheses

The various hypotheses that explain rings around the giant gaseous planets differ primarily in their account of the relation between the ring particles observed today and the primordial ring material. According to one hypothesis, a single large body was fragmented into myriad pieces when it came close to a planet and the fragments then formed rings. The body may have been a large meteoroid that suffered a chance gravitational encounter with the planet, or it may have been a moonlet that formed in the planet's envelope. In either case the agent of fragmentation would have been tidal disruption: the shearing force that arises because the gravitational attraction exerted by the planet on the body is greater for the parts of the body closer to the planet than it is for the parts farther away. The creation of Saturn's rings by tidal disruption was first proposed by the French mathematician Edouard Albert Roche in 1848. Roche had calculated that tidal forces exceed the cohesive self-gravitation of a liquid moon if the moon comes closer than about 1.5 Saturnian radii to the surface of the planet. This disruption threshold—the Roche limit—lies close to the outer edge of the main rings of Saturn.

It is quite unlikely, however, that a moonlet near Saturn would have been liquid. It would have been solid, and a solid moonlet is held together not only by self-gravitation but also by the forces that order the atoms in crystalline matter. According to Hans R. Aggarwal and Verne Oberbeck of the Ames Research Center of NASA, a solid moonlet smaller than about 100 kilometers in diameter cannot be tidally disrupted at any distance from the surface of a planet. Moreover, a larger solid moon cannot be disrupted at a distance greater than .4 planetary radius from the surface. That distance places the disruption threshold inside the inner edge of the main rings of

Saturn. It also is unlikely that the tidal disruption of a stray meteoroid could yield ring particles near Saturn. The particles, like their parent body, would have velocities sufficient for them to escape from the planet's vicinity.

There is nonetheless a subtle way in which tidal forces could have been important. As Roman Smoluchowski of the University of Texas at Austin has shown, the gravitational attraction of particles of equal size is insufficient to hold them together against disruption by tidal forces inside the classical Roche limit (the limit calculated by Roche for a liquid moon). In contrast, two particles that differ greatly in size can resist tidal disruption at distances well inside the classical limit. As it happens, the limit set by the tidal disruption of two particles of equal size and the limit set by the tidal disruption of two particles of unequal size lie close to the outer and inner edges of the ring systems around Jupiter, Saturn and Uranus. Within the outer disruption limit particles may have accreted, but so slowly that they were kept from aggregating into large moons. Within the inner disruption limit growth may have been almost impossible.



EVOLUTION OF A RING SYSTEM probably began in the early solar system, when the contraction of a rotating gaseous cloud into a giant planet such as Saturn left behind a gaseous envelope strung out by the centrifugal force associated with its rapid rotation (*a*). The particles accreting in the envelope must have orbited the planet, but they also had random motions that caused them to collide (*b*). The collisions were inelastic: they deformed the particles and also heated them. The corresponding loss of kinetic energy decreased their vertical motion. The collisions between two particles at nearby radial distances had an additional effect. In each such collision the inner particle would have been orbiting the planet faster; it would hit the outer particle from behind. The resulting transfer of momentum would raise the orbit of the outer particle and lower the orbit of the inner one. Thus the envelope spread horizontally. Ultimately a flat disk emerged in which the random velocities of the particles with respect to one another had only about a ten-millionth the magnitude of their mean orbital velocity (*c*). It is thought the smallest particles in the rings today result from the collisional erosion of the larger particles.

The second major hypothesis regarding the history of ring particles was suggested by Eugene Shoemaker of the U.S. Geological Survey. It postulates that a single large moon in the ring region (or perhaps a number of moons) collided catastrophically with a stray meteoroid. The photographs of the moons of Jupiter and Saturn made by the Voyager spacecraft do in fact show that the moons are scarred by a large number of craters produced by high-velocity collisions. Mimas, one of the smaller moons of Saturn, has a crater spanning a third of one hemisphere. The collision that made this crater must have come close to destroying Mimas. Nearer Saturn two objects with a diameter of about 100 kilometers occupy almost identical orbits. They may be the largest fragments of a catastrophic collision between a moon and a giant meteoroid.

There are several reasons why catastrophic collisions may have occurred preferentially in a region to be occupied later by rings. First, the major moons of Jupiter and Saturn tend to be smaller at distances closer to their planet. At a given energy of collision small moons are more likely to fragment than large ones. Second, the gravitational field of a planet focuses the trajectories of meteoroids, so that the flux of meteoroids passing close to the planet is significantly greater than the flux at increasing distances.

A final hypothesis regarding the history of ring particles postulates that the larger bodies in the rings are simply the result of the limited extent of the accretion of matter in the circumplanetary envelope at distances close to the planet. The accretion began with the cooling of the envelope and the resulting condensation of gaseous matter into tiny solid grains. Gravitational forces and gaseous drag caused the grains to settle into the equatorial plane of the envelope. There the grains continued to grow by the condensation of vapor onto their surface. Such growth could bring them to sizes as large as a few meters. The particles that make up most of the visible rings of Saturn range in size from a few centimeters to a few meters. They may be the product of such a process. Any moonlets in the rings would then be the local products of a stage of growth in which the meter-size bodies accreted further as the result of gentle collisions.

The ring particles in all three ring systems are small and numerous. According to the accretional hypothesis, there are several reasons why this is the case. First, the undisturbed formation of tiny grains could not begin at a given distance from an incipient giant planet until the planet had shrunk to a size inside that distance and the circumplanetary envelope had cooled sufficiently. Thus less time was available for the formation of grains near the planets than was available at greater distances. Second, the tiny grains near Jupiter could form only from the relatively rare, high-temperature condensates that were available. Finally, the arrival of a moonlet at a certain size would mean that its overlapping resonances spanned a width comparable to its dimension. Fresh material could no longer reach it, and so it would stop growing. In Saturn's rings the calculated limit to growth is a few kilometers to some tens of kilometers. Rather different conditions must have prevailed at greater distances from Saturn and the other giant planets, since bigger moons formed there.

Continuing Erosion

What about the small particles in the ring systems? We have already noted that gaseous drag causes micrometer-size particles to spiral from the outer edge of the bright ring into the atmosphere of Jupiter in a mere few hundred years. Plainly such particles could not have survived from the time the planet had a gaseous envelope. They must be forming today. According to Joseph A. Burns of Cornell, they result from the erosion of larger bodies in or near Jupiter's bright ring.

Ring particles larger than a centimeter or so are not readily destroyed by their collisions with interplanetary micrometeoroids. Instead each collision excavates a tiny crater around the point of impact, and an amount of matter 1,000 to 10,000 times greater than the mass of the impacting body is ejected. Many of the micrometer-size particles in the ring systems may originate, then, as ejecta. It can be estimated that if a moonlet is smaller than about 10 kilometers in diameter, most of the ejecta resulting from a collision with an interplanetary body can escape from the moonlet's gravitational field. The ejecta that escape from the moonlet would lack the energy to escape from the planet around which the moonlet orbits; thus they would take up orbits in the rings. (The continuing erosion of a parent population might also be a source of bodies in Saturn's rings on the order of a centimeter or a meter in size.)

In sum, the moonlets in the rings and also the largest ring particles probably date back to the early history of the solar system: they are contemporaries of the moons of the giant planets. The smallest ring particles are forming even now. It is suspected that the large moons of the outer solar system and also several planets (including the earth) formed by the accumulation of many bodies of smaller size. Surely among the multitudes of particles in the rings similar processes are being enacted on a small scale today. The ring systems thus offer a double challenge. One seeks to deduce the processes that made them and then one seeks to use this knowledge to gain insight into how the solid moons and planets formed.