Planetary Rings Explained and Unexplained

Theoreticians are understanding more and more details of ring structure, but major problems remain

Toulouse. What would happen if some titanic force were to crush an icy satellite into a billion billion pieces and toss them back into close orbit around the planet? For more than a century the answer from both theory and observation had been obvious—they would form a broad, flat disk of tiny satellites, much like the one around Saturn. The disk might be subdivided in a theoretically predictable way, as Saturn's seemed to be, but otherwise it would be unremarkable.

Then, beginning in 1977, a string of discoveries startled researchers into the realization that a cloud of orbiting particles can put more than a few unexpected twists in classical Newtonian mechanics. Rings can be startlingly narrow like Uranus's, evanescent but self-regenerating like Jupiter's, or broken into a myriad of rings within rings, as Saturn's appear to be. At the end of August, planetary scientists and theoreticians met in Toulouse,* France, to compare the bewildering array of new kinds of ring structure with possible physical causes. They had mixed success.

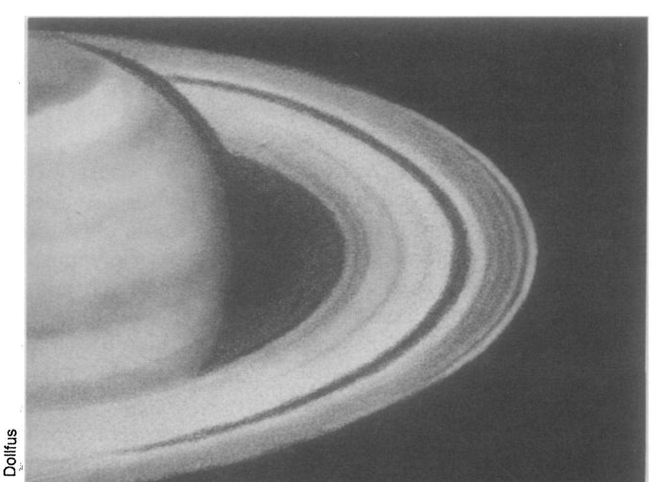
The complexity of planetary rings was not wholly unanticipated. Reporting numerous subdivisions in Saturn's three main rings has been in and out of vogue over the past few centuries, as was the sighting early in this century of canals on Mars. But within the past few decades, planetary observers had consistently put enough fine structure in their drawings of the rings to convince some researchers that at least part of the structure might be real. Photometric observations from Earth and the Pioneer Saturn spacecraft likewise suggested that some light leaks through thin spots in even the densest parts of the rings.

In 1867, Daniel Kirkwood provided a theory of subdivisions in the rings that has been the standard textbook explanation for a hundred years. The classical application of Kirkwood's theory to rings is the explanation of the gap between the A and B rings first observed by Jean Dominique Cassini in 1675. Kirkwood pointed out that ring particles in the Cassini division, each of which would follow its own circular orbit about Saturn, would repeatedly overtake the more distant, slower moving satellite Mimas at the same point in its orbit. That is, Mimas and these particles would be in resonance because their orbital periods have the whole-number ratio 2:1. Each time a ring particle overtook the immensely larger Mimas, it would feel the satellite's gravitational tug at the same point in its orbit.

These periodic tugs, like the well-timed pushes that send a swing ever higher, perturb particles in resonance with Mimas into noncircular orbits, causing them to collide more often with particles outside the resonance. The result, according to simple resonance theory, is the clearing of a gap. It seemed to work for some qualitative aspects of the asteroid belt and the Cassini division; the great width of the latter had never been satisfactorily explained. Some observers even found gaps or divisions at other satellite resonances.

Resonance theory still stands after the onslaught of spacecraft observations, but its new applications have yielded a greater variety of ring features than Kirkwood ever dreamed. Resonances do create gaps, but they also create sharp edges, spiral density waves, and bending waves. First theoretically proposed in 1978 by Peter Goldreich of the California Institute of Technology and Scott Tremaine of the Massachusetts Institute of Technology to help explain the width of the Cassini division, a spiral density wave was first identified in Voyager images of the rings by Jeffery Cuzzi of NASA's Ames Research Center and Jack Lissauer and Frank Shu of the University of California at Berkeley. Such a wave, which appears as alternating, narrow bands of brightness and darkness, is actually a single compressed band of particles that tightly spirals outward from the resonance that sets it in motion, like a groove on a phonograph record.

Unfortunately, most of the observed ring structure could not be attributed to density waves. Voyager 2 produced the most detailed view of ring structure by recording the flickerings of a star passing behind the rings. Larry Esposito, Michael O'Callaghan, and Robert West of the University of Colorado searched the photopolarimeter's 800,000 data points from this stellar occultation (one every 100 meters on the ring) and found only 50 spiral density wave trains, hardly enough to account for the estimated 10,000 or more features of Saturn's rings. They found all of the spiral density waves associated with the strongest resonances and proportionately fewer of the weaker ones, allowing them to estimate that only 75 should ever be identifiable in the Voyager data. Nearly all of these spiral density waves fall in the A ring, explaining much or even most of the structure there, but resonances of major satellites interior to A are few and far between,



Another view of Saturn's rings

A drawing made by Audouin Dollfus in 1960 using the Pic du Midi 60-centimeter refractor telescope. Similarities between this view and Voyager images suggest that telescopic observers did indeed see the main rings as composed of many subdivisions.

*Planetary Rings, colloquium number 75 of the International Astronomical Union, held 30 August to 2 September 1982 at the National Center for Space Studies, Toulouse; André Brahic, chairman.

0036-8075/82/1008-0141$01.00/0

and those of small, close-in satellites become rapidly weaker there.

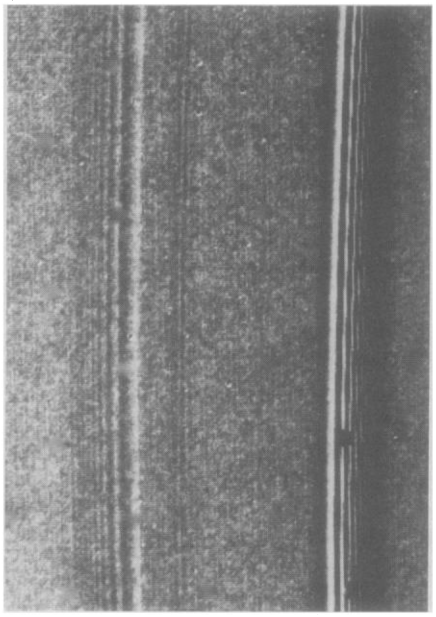
A variation on the spiral density wave creates an interesting if not numerically significant feature called the bending wave. Lissauer, Shu, and Cuzzi found that the Mimas 5:3 resonance not only creates an outward-spiraling density wave, but also, because of Mimas's slightly inclined orbit, a ripple in the ring. Unlike a ripple from a rock dropped in a pond, a bending wave propagates inward, revealing itself in Voyager images by the shadows cast by its peaks.

Another kind of ring structure produced by resonances is startlingly sharp ring edges, such as the outer edge of the B ring (the inner edge of the Cassini division). Across a distance of less than 1.5 kilometers, one of the densest, most opaque parts of the rings falls away to nearly empty, clear space. Mimas, which circles more than 66,000 kilometers farther out, has traditionally been credited with clearing the Cassini division through its 2:1 resonance. Why the gap should be so wide is still unclear, but an explanation offered by Nicole Borderies of Caltech, Goldreich, and Tremaine seems to suffice for the creation of its inner edge.

Their explanation involves the transfer of angular momentum. In an undisturbed ring, the inevitable collisions of ring particles transfer angular momentum outward smoothly across the ring disk, causing the particles and the disk to spread radially. At Mimas's 2:1 resonance, that angular momentum is transferred to Mimas through tides that Mimas raises in the ring.

According to conventional thinking, that angular momentum would be gradually removed from the ring over a considerable distance. Because the flow of angular momentum is normally proportional to the mass of particles in a given part of the ring, the ring itself would be seen to taper off gradually along with the decreasing outward flow of angular momentum. But according to the Borderies, Goldreich, and Tremaine theory, at the Mimas 2:1 resonance the flow can be either outward or inward depending on the location along the edge. The net flow decreases to zero, the requirement for an edge, but there are still high flows up to the edge, the requirement for a dense ring. The resulting barrier could be so efficient as to have dammed the outward drifting B-ring particles for the age of the solar system, Goldreich says.

Theorists are a bit troubled that they do not know exactly why one resonance produces a spiral density wave, another a sharp edge, and a third one of the more subtle narrow bands or gaps seen at resonance locations. "That is a delicate question," as Tremaine puts it. The strength of the resonance, which is proportional to the satellite's mass and distance, seems to be an important but not the sole determinant. The 7:6 resonance of the larger of the two co-orbiting satellites (not 1980S28, as previously supposed) forms the sharp outer edge of the A ring, Tremaine notes, but its nearly equivalent 6:5 resonance produces only a minor feature.



One resonance, two waves

On the left is a bending wave, which creates 1- to 2-kilometer-high ripples in the ring, and on the right is a spiral density wave. Both are generated by the same 5:3 gravitational resonance with the satellite Mimas, but are separated by the gravitational effect of Saturn's oblateness. Data noise has spotted the image.

No matter what controls the effectiveness of satellite resonances, there are simply not enough of them that reach into the B and C rings to explain the profusion of features that Voyager found there. If bodies outside the rings would not work, the reasoning went after the Voyager 1 flyby, then maybe bodies inside the rings themselves would. The search for "embedded moonlets" was on (*Science*, 5 December 1980, p. 1111).

The idea was that oversized ring particles, perhaps 10 kilometers across, would plow through the rings and gravitationally push aside smaller particles. Goldreich and Tremaine had proposed this counter-intuitive mechanism of gravity-that-repels to explain the confinement of the narrow rings of Uranus (*Science*, 5 October 1979, p. 38). The apparent repelling effect of gravity depends on ring particles colliding between passes by the moonlets. Voyager 1 dramatically supported the moonlet herding theory when it discovered two small satellites herding the narrow F ring. Why not the same mechanism for the narrow ringlets found in gaps? Or most of the structure of the B ring? But the search of Voyager 2 images failed to discover any moonlets in the most likely place, the inner Cassini gap. Things looked bleak for embedded moonlets.

At Toulouse, things got worse for the widespread application of the herding theory before they got better. Esposito and his group searched stellar occultation data from 14,000 kilometers of the outer B ring for any sign of the star shining through empty gaps cleared by moons too small to be detected by Voyager. They found only 105 data points (10 kilometers worth) where the rings were transparent, but none of these possible breaks in the B ring was more than 200 meters wide. Theorists had estimated the minimum diameter of moonlets responsible for ring structure detected by Voyager as 2 kilometers, Esposito pointed out.

There was a possible way out of the negative stellar occultation search for gaps. Gaps cleared by moonlets could be partially filled by fine particles, which respond more to the frictional effects of particle collisions than to the gravitational herding of moonlets. But Leonard Tyler of Stanford University told *Science* that the other Voyager occultation, that of the Voyager spacecraft by the rings as seen from Earth, also failed to detect narrow gaps in the distribution of larger particles. Voyager beamed microwave radio signals of two different wavelengths (3.6 and 13 centimeters) back to Earth through the rings. Particles 1 to 4 centimeters in diameter would tend to obstruct the shorter wavelength signal, but the radio occultation group cannot find any gaps wider than 2 kilometers at that wavelength.

No one had a way around that combination of observations, but if embedded moonlets no longer appear likely in the B ring, after Toulouse they seem almost certain to form at least one set of ringlets in a gap. Cuzzi and Richard Terrile of the Jet Propulsion Laboratory (JPL) reported that, while working independently, they each discovered that the edges of the Encke division are wavy or scalloped. From the scalloping's wavelength of about 1500 kilometers and amplitude of 5 to 10 kilometers, both Terrile and Cuzzi concluded that there must be at least one moonlet in the Encke division, presumably shepherding one or both of the ringlets there. Cuzzi and Terrile do not agree on details, but something is obviously there. In a three-moonlet arrangement, the particles orbiting at the inner edge of the gap move outward until they can transfer angular momentum to the first moonlet; it moves outward until it can transfer angular momentum to the particles of the first ringlet; and so on, until the momentum passes on to the outer edge of the gap.

The inferred but unseen Encke division moonlets lend support to the presumption that all narrow, dense ringlets are shepherded by moonlets. There is other support. Uranian rings, the F ring, ringlets in gaps, and ringlets in the C ring are at times not only narrow but also kinked, noncircular, or lumpy. They often share a common characteristic in stellar and radio occultation data as well, namely, a W shape in the opacity curve. Apparently, smaller particles produce the W shapes by tending to pile up toward the edges of ringlets. Despite these similarities, no moonlets other than the F-ring shepherds have been seen, and no scalloping of gap edges other than Encke's has been found. Tremaine notes that other gap moonlets would not have to be as large as Encke's and, therefore, might not induce detectable scalloping. The failure to find inner Cassini moonlets herding ringlets or clearing a gap still disturbs him, but "I don't know of anything else that could do it," he says.

Resonances and moonlets may explain some of the ring features found by Voyager, but Esposito argued at Toulouse that there is no single, dominant mechanism evident in the most detailed Voyager data. The Colorado group displayed a power spectrum analysis of their stellar occultation data that did not even reveal a major role for spiral density waves, which typically produce 10- to 50-kilometer structure. The most important organization of particles occurs on the scale of the three main rings and their major subdivisions, Esposito emphasized, and below 20 kilometers there is only random or chaotic structure generation.

A mechanism that might help to account for this chaotic situation received a bit of a boost at the meeting. First proposed in 1981 by William Ward of JPL and by Douglas Lin and Peter Bodenheimer of Lick Observatory, the diffusive instability theory is a leading contender for a mechanism to create structure in the B ring, where perhaps three-quarters of the total ring mass resides.

How Thin Is Thin?

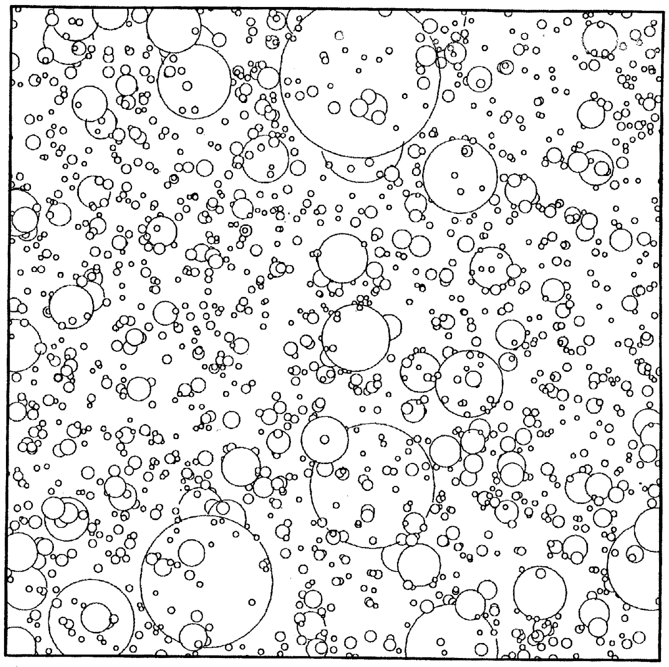
Saturn's main rings are obviously thin. They easily encircle the second largest planet of the solar system, but disappear when viewed edge-on from Earth. Their relative thinness has been compared to that of a sheet of tissue paper the size of a football stadium. Estimates made from Earth of their exact thickness have plummeted from Herschel's upper limit of 300 kilometers to perhaps 1 to 2 kilometers. At the planetary ring meeting in Toulouse, discussion of ring thickness centered around spacecraft data that require an upper limit of 200 meters and suggest an actual ring thickness of 30 to 50 meters. Theoretical calculations favor no more than 10 to 20 meters. For a structure spanning 270 million meters, that is truly thin.

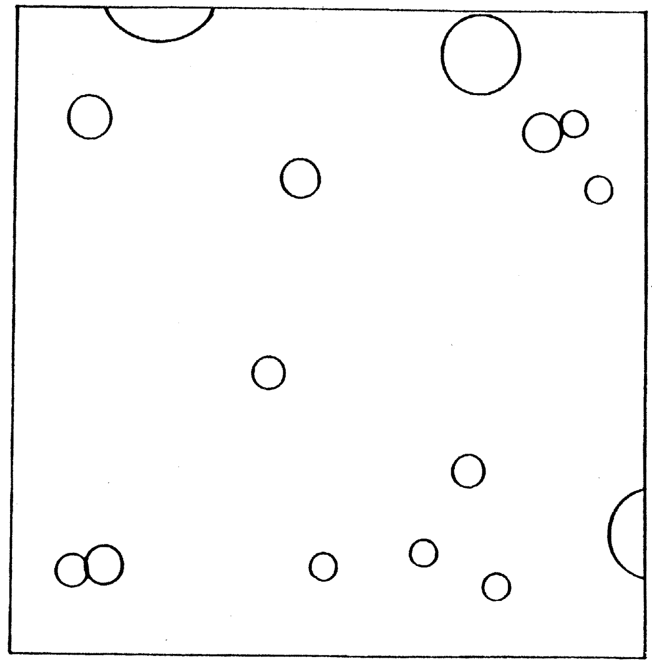
Rings by their very nature are thin. Collisions between ring particles remove kinetic energy from the particles, damping their orbits around Saturn into its equatorial plane. But even the most sophisticated Earth-based observing techniques have failed to squeeze the thickness much below the theoretically unlikely figure of 1 kilometer. Bruno Sicardy and his colleagues at the Observatory of Paris at Meudon reported that their photometric observations in March 1980, when the rings appeared edge-on from Earth, yielded a thickness of 0.6 to 2.0 kilometers. But they have an idea what the problem might be. Rather than assuming a uniformly thick ring, as some have in the past, the French group and others suggest that they are seeing a thin ring plus imperfections that add to its apparent thickness. These imperfections include warping and rippling of the ring by external gravity fields, the faint halo of the E ring, satellites orbiting just outside the main rings, and moonlets embedded in the rings. A true measurement of ring thickness, sought by telescopic observers for centuries, seems out of reach from Earth.

From the point of view of the Voyagers, the rings appear even thinner. There having been little time to look as the Voyagers whizzed through the ring plane, researchers reported two independent, direct measurements of thickness based on views through the rings. Essam Marouf and Leonard Tyler of Stanford University calculated an upper limit from the diffraction pattern of Voyager's radio waves as the spacecraft passed behind a sharp ring edge. Arthur Lane of the Jet Propulsion Laboratory and his photopolarimeter team calculated another upper limit from the amount of smearing of light from the star δ Scorpii as it passed behind several sharp edges. Both methods produced an upper limit of 200 meters.

Researchers have made indirect calculations of even thinner rings on the basis of the reaction of the rings to perturbations by satellites. Jack Lissauer and Frank Shu of the University of California at Berkeley and Jeffrey Cuzzi of NASA's Ames Research Center calculate a thickness of 30 meters from the behavior of a bending wave, an inward-moving ripple touched off by gravitational effects of the satellite Mimas. Larry Esposito of the University of Colorado estimated a thickness of about 50 meters using Earth-based observations of ring brightness plus Voyager observations of waves in the rings. If the depth of the Atlantic Ocean were in the same proportion to its 4000-kilometer breadth as this thickness is to the breadth of the rings, the abyssal depths of the Atlantic would not quite reach 1 meter. You could never get in over your head.

Thirty to fifty meters may still be an overestimation of typical ring thickness, according to some theorists. Peter Goldreich of the California Institute of Technology argued at Toulouse that all of these calculations depend on observations of the most highly perturbed parts of the rings—sharp edges, spiral density waves, and bending waves. These are the areas, he said, that should be the thickest because whatever creates these features also pumps energy into the rings that increases turbulent particle motion and puffs up the ring. Less perturbed areas of the rings might reach a few tens of meters in thickness at most. The bulk of the mass of the rings, which resides in the meter-size particles, may yet be found to form a ring 10 meters or less thick, Goldreich told *Science*; smaller, centimeter-size particles might rise above such a ring to thicken its appearance. In any case, researchers are now agreed that Saturn's rings are very thin indeed.—R.A.K.





Close-ups of two rings

These are computer-drawn representations of ring particles in the A ring (left) and the C ring (right). Both areas are 0.5 meter on a side. The smallest particles shown are 1 millimeter in radius. The size and number of particles larger than 1 centimeter in radius are based on radio occultation data from Voyager spacecraft (Tyler and others). Particles smaller than 1 centimeter in radius were inferred to be present in the A but not the C ring by comparing the radio data with optical data from the Voyager stellar occultation (Esposito and others). The assumption is made that the observed trend in particle size distribution extends to the smaller particles, which is consistent with observations. Meter-size particles are found in both rings but do not appear here. In the C ring, one particle having a radius in the range of 2 to 4 meters would be found in every 1000 square meters; in the A ring, a particle of similar size would be found in every 100 square meters. [Source: E. C. Stone, Caltech]

Their theory depends on how icy ring particles rebound from collisions with each other as the speed of collision increases. If ring particles really did behave the way the theory requires, they would have a tendency to clump together in dense rings separated by open gaps.

Initial attempts to apply the theory to Saturn's B ring produced perfectly clear gaps, in embarrassing contrast to observation. The latest refinement of the theory, presented by Alan Harris of JPL and Ward, produces a more realistic structure because the use of a bimodal particle distribution allows smaller particles to fill the gap. The next step would be to use a continuous distribution of sizes resembling that of the ring. "It's a physically correct mechanism," says Goldreich, "and it smells like some form of it might be right for the B ring." The problem, he notes, is that the theory depends crucially on the physical properties of ring particles—such as whether they are soft snowballs, solid ice, or something in between—that researchers know next to nothing about.

The properties of ring particles themselves received scant attention here, no doubt reflecting a dearth of new data, but there was another hint that understanding ring structure may require a much better understanding of the particles. Cuzzi reported that in the denser parts of the B ring the brightness variations of ring features that are 100 to 200 kilometers across cannot be explained by the amount of particle surface area reflecting the sunlight. Because the particles seem to reflect light in the same manner throughout these areas, Cuzzi concludes that the differences in brightness must result from differences in albedo, the efficiency of light reflection. That requires differences in surface properties, he notes, such as color, chemical composition, or texture. There are few ideas about how these differences might be created or maintained.

One physical property of ring particles that is much better known after Voyager is size, which also seems to play a role in determining ring structure. Data from Voyager imaging, the radio occultation, and the stellar occultations are being combined to show how particles of different sizes have different distributions across the rings. As Tyler noted, "The ring that you see depends on the wavelength that you use." By radio occultation, W shapes seem to consist of smaller particles (1 to 4 centimeters), but some W shapes are seen in radio and stellar occultations and others only in stellar occultations, implying the presence of even smaller particles. The F ring has a narrow, dense core of "marbles" embedded in a broader band of fine particles that are invisible at radio wavelengths. And even the A ring seems to have more centimeter-size particles toward its edges than near its center.

The most fundamental problem considered at the colloquium was one of the oldest in ring studies—why is there an A, a B, and a C ring? The mechanism that frustrates the natural spreading of ring particles at the outer edges of A and B seems to be strong resonances. But these do not work at the inner edges of A and B, or at the boundary of B and C. And the outer-edge resonance of A is only a temporary fix; nothing so puny as the larger co-orbital satellite can hold back the spreading of the rings without being pushed outward itself. The problem is that not enough spreading has occurred to fit theory, unless the near-ring satellites have been able to pass on angular momentum from the rings to a larger body.

Goldreich conceded that he had spent a month looking for a resonance relation that would connect these satellites to Mimas and finally to Tethys, a suitably massive anchor for the rings. He found none, and no one else had even a tentative suggestion. The alternatives are that the rings are much younger than the 4.5-billion-year age of the solar system, an idea philosophically abhorrent to most, or that theorists do not fully understand satellite resonances. It would not be the first time that rings have pushed theorists to new understanding of orbital dynamics.—RICHARD A. KERR