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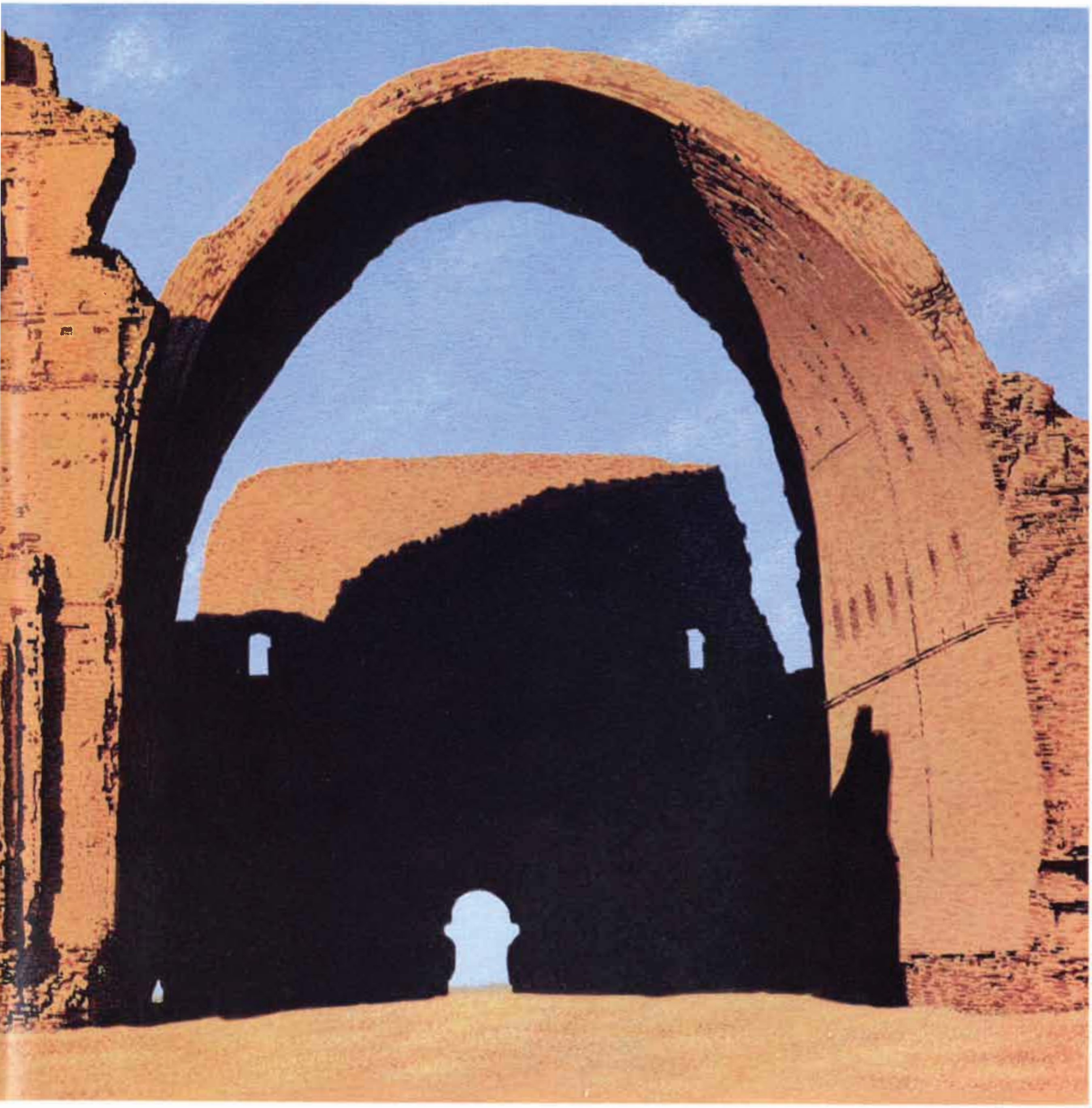

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The Rings of Uranus

Why are they so narrow and dark? Findings from the Voyager 2 *encounter suggest that the austere ring system may be only a fleeting stage in a continuing saga of creation and destruction*

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In 1977 an unexpected experimental result led to the surprising but inescapable conclusion that the planet Uranus is surrounded by a family of narrow, dark rings unlike any seen before. Subsequent accumulation of more information about the rings raised several fundamental questions. Why are the Uranian rings so different from the broad, bright rings of Saturn? Why are some of them noncircular? Why do they have varying widths, sharp edges and vast reaches of empty space between them?

The *Voyager 2* encounter with Uranus in January, 1986, was designed to test dynamical models of ring structure by determining precisely the locations of the known rings, searching for new rings and observing the size and detailed distribution of particles within the individual rings. Perhaps most important, the spacecraft was also to search for small ring moons orbiting between the rings that are thought to shepherd the ring particles, or keep them in orbit, by exerting gravitational forces on them.

The cameras on *Voyager 2* discovered one new narrow ring and about 100 almost transparent bands that are invisible from the earth. Several partial ring arcs were also seen. The particles in the known rings are larger than had been expected, ranging between a softball and an automobile in size (between 10 centimeters and a few meters). The particles in the newly discovered dust bands, in contrast, are much smaller (roughly .02 millimeter) and their locations are not obviously related to the previously known rings. Ten small moons were discovered that lie within the orbit of Miranda, which is the closest to Uranus of the five main moons [see "The Moons of Uranus," by Torrence V. Johnson, Robert Hamilton Brown and Laurence A. Soderblom; SCIENTIFIC AMERICAN, April]. Two of the new moons appear to shepherd the particles in the outermost ring, but no ring moons of the sizes that had been expected were found anywhere near the other rings. The main rings and new moons are charcoal black.

The information *Voyager 2* transmitted across some three billion miles of space has already verified many aspects of the dynamical models of the Uranian rings. At the same time the new results have highlighted some difficulties with the models. The information has provided new perspectives on the rings of Uranus as well as the closely related ring systems of Saturn, Jupiter and Neptune.

The discovery of the Uranian rings was made during a stellar occultation, in which the brightness of a star is monitored as a planet passes between it and the earth. The main advantage of the technique, which was developed to study the atmosphere of planets, is its high resolution, because of the small apparent size of stars. Features as small as one kilometer to five kilometers can be distinguished from the earth during stellar occultations; in comparison, the best telescopic views of the outer planets have relatively poor resolutions of thousands or tens of thousands of kilometers.

On March 10, 1977, several groups of investigators observed the occultation of the star SAO 158687 by Uranus. To calibrate their instruments they started their observations well ahead of the predicted occultation and continued for as long as possible afterward. They were surprised to find that the starlight was sharply blocked during several short intervals both before and after Uranus passed in front of the star. At first the brief occultations were attributed to a belt of asteroids around the planet. The notion of rings was initially rejected because the occultations were so brief that any rings would have had to be much narrower than Saturn's. As the data from the independent observers were compared during the next few days, however, it became clear that each occultation on one side of Uranus was matched by another occultation on the other side. The observations could be explained only by the conclusion that the planet is surrounded by a family of threadlike rings.

During the next few years observations of more than 200 stellar occultations by Uranus revealed nine narrow rings, all of which lie within one planetary radius of the top of the Uranian atmosphere. Following the differing notation of the discoverers the rings are called (in order of increasing distance from Uranus) 6, 5, 4, alpha, beta, eta, gamma, delta and epsilon. Most of the more recent occultations were observed by James L. Elliot and Richard G. French of the Massachusetts Institute of Technology and independently by Philip D. Nicholson of Cornell University, along with their collaborators. Their work disclosed the properties of the ring orbits with an extraordinary degree of precision. In fact, even the tiny perturbations of Uranus itself by its major moons are detectable in the data.

The rings are not all circular, nor do they all lie in the plane of Uranus' equator. Their widths range from less than two kilometers to nearly 100 kilometers. In comparison, the broad, main rings of Saturn essentially fill a region that is about 60,000 kilometers wide. The epsilon ring of Uranus, which is the outermost one and the largest, ranges in width from 20 to 96 kilometers. This variation in width is not random: the width increases in proportion to the distance of the ring material from Uranus. In other words, at its nearest point to Uranus the epsilon ring is narrowest and almost opaque. At its farthest point it is five times wider and five times more transparent. The alpha and beta rings show similar behavior in that orbits with-

URANIAN RINGS are seen in an image obtained by *Voyager 2* from a distance of about a million kilometers as the spacecraft approached Uranus. The threadlike rings, which are for the most part densely packed with particles, are only a few kilometers wide. They are separated by hundreds of kilometers of virtually empty space. A new ring designated 1986U1R is barely visible between the outermost ring (epsilon) and the next bright ring (delta). The rings reflect only 1 percent of the incident light.

in each ring are nested together. The alignment of the long axes of the ring orbits varies randomly from one ring to the next.

The next three most prominent rings (eta, gamma and delta) have very narrow cores only a few kilometers wide, and eta and delta have broader and more transparent components as well. Although these rings are circular on the average, each of them shows apparently random variations in radius and width. The variations are even larger than the average width of the rings themselves.

The apparently random "wiggles" in the radius and width of the eta, gamma and delta rings are similar to the behavior of some narrow rings in the Saturnian system. Saturn's *F* ring and two ring arcs in a large gap called Encke's division are strands only a few kilometers wide and show highly irregular kinks and wiggles as well as a large fraction of microscopic dust. These properties have been attributed to vigorous ongoing collisions brought about by gravitational forces exerted by nearby moons.

Knowing the widths of the Uranian rings and how little light they reflect, investigators determined even before the *Voyager 2* encounter that the particles in the rings must be very dark; it appears that a flat surface of particle material would reflect less than 5 percent of sunlight falling directly on it. The five principal moons of Uranus, in contrast, have a reflectivity of about 30 percent; the earth's moon and Mars have a reflectivity of approximately 10 percent.

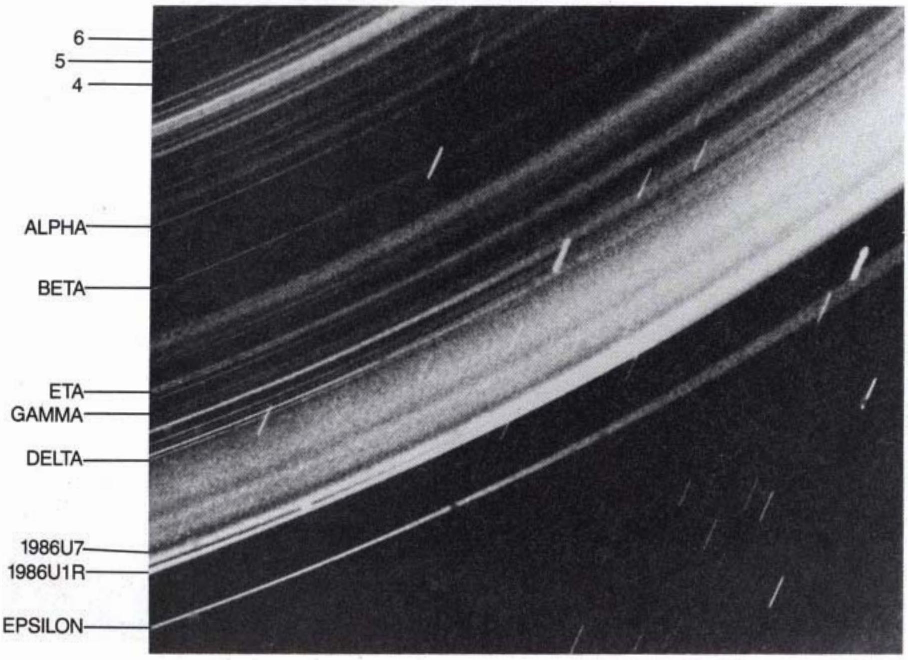
The *Voyager 2* encounter provided the first close view of the rings of Uranus, a view that now allows the Uranian rings to be compared with those of the other giant planets (Jupiter and Saturn) visited by the spacecraft. As *Voyager 2* was drawn ever closer to Uranus—a nearly featureless, gas-enshrouded planet 17 times as massive as the earth—its attention was divided among the Uranian atmosphere, rings and moons. Although the nine main rings were known to be too narrow and dark for the satellite's cameras to study in much detail, noticeable differences among the rings were nonetheless detected [*see illustration on preceding page*].

The quality of the images produced during the mission is particularly remarkable considering the difficulties that were encountered. Making a picture of the rings is comparable to making a picture of charcoal briquettes on a black background at the base of a Christmas tree lighted by a single bulb at the top, employing a camera loaded with film rated ASA 1. Such an image would require an exposure of 15 seconds. Unsmeared images of the rings would have been impossible to obtain without major improvements made painstakingly over several years by the *Voyager 2* spacecraft engineers [see "Engineering *Voyager 2*'s Encounter with Uranus," by Richard P. Laeser, William I. McLaughlin and Donna M. Wolff; Scientific American, November, 1986].

Additional images were obtained as *Voyager 2* crossed the plane of the rings and peered through them nearly sideways. After the spacecraft had streaked by the planet, and while the sun was hidden behind the planet, a single long-exposure image was made looking at only a small angle away from the sun. The image reveals about 100 very diffuse, nearly transparent bands of microscopic dust surrounding the known rings [*see illustration on this page*].

Like earthbound observatories, *Voyager 2* also made use of stellar occultations. The procedure was similar to the one that led to the discovery of the rings. In this case, however, the resolving power was much greater because the spacecraft passed so close to Uranus. The closeness of the approach overcame a fundamental limitation of all occultation studies: the washing out of shadows cast by the object of interest. Shadows cast by smaller objects or structural features in rings are easily degraded by diffraction and can be seen only at such close range. Finally, as *Voyager 2* passed behind the rings its radio signals to the earth were also occulted, providing another, independent means of making high-resolution observations.

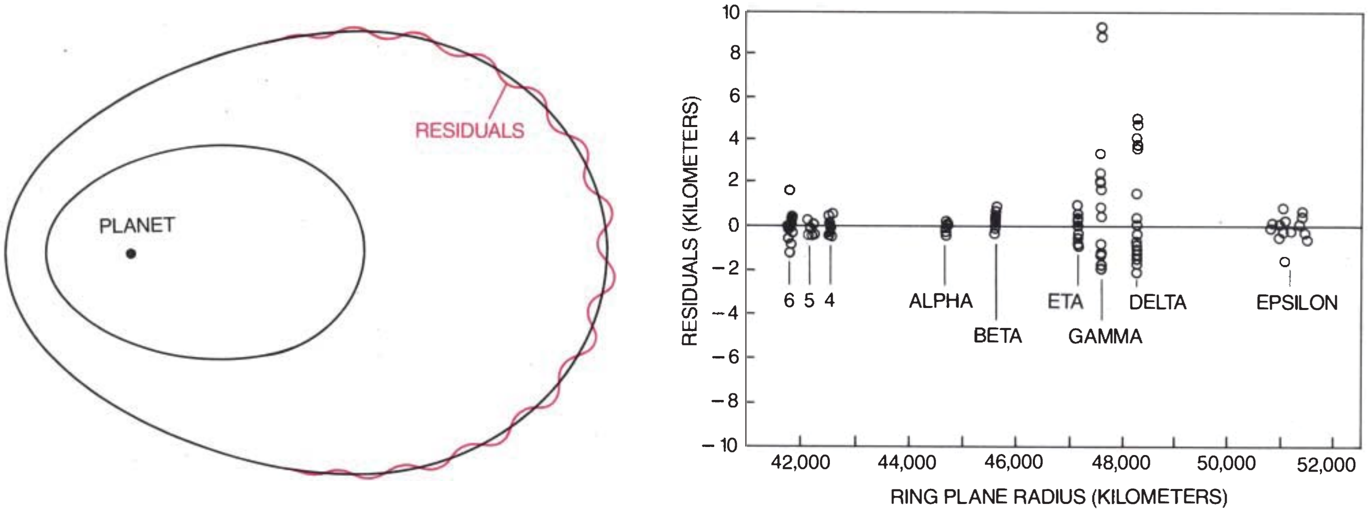
The best *Voyager 2* images revealed quantities of microscopic dust widely spread throughout the rings of Uranus. Such dust is of special interest because tiny particles in and around planetary rings are rapidly removed as a result of erosion by micrometeoroids and radiation-belt electrons. The existence of the dust implies that a local, long-lived source consisting of more massive particles must exist.



DIFFUSE BANDS of microscopic dust were recorded in a single long-exposure image after *Voyager 2* had streaked by Uranus. Nearly 100 bands are evident. The outermost feature is the epsilon ring, which seems to be isolated from the bulk of the dust. Here the ring 1986U1R is the brightest feature, indicating that it has a large component of dust.

Relatively little of the dust (much less than 1 percent by fractional area) is found in any of the main rings, however. The dustiest feature, in fact, is one of the most prominent new rings, designated 1986U1R. The lack of dust in the main rings came as a surprise. Analogies with several of the narrow rings of Saturn had led workers to expect that at least the eta, gamma and delta rings of Uranus would contain noticeable dust. *Voyager 2* revealed, however, that the rarefied upper atmosphere of Uranus is considerably denser than had been thought. Apparently the atmosphere drags microscopic dust particles out of their orbits in only a few hundred years, much as the upper traces of the earth's atmosphere caused the demise of the much larger (but much closer) *Skylab* orbiter.

Comparing the transparency of the rings at the two radio wavelengths



TYPICAL RING can be modeled by assuming its edges are defined by a combination of smooth elliptical orbits and random "wiggles" (*left*). The wiggles are inferred from residuals: differences between observation and smooth ring models. The residuals associated with the nine main rings of Uranus are as large as several kilometers (*right*). The various residuals of the eta, gamma and delta rings are so large that they are thought to have arisen from gravitational perturbations exerted by nearby moonlets.

transmitted by *Voyager 2* as it passed behind the rings led to firm knowledge of the ring particles. The sizes of the largest particles in the rings are on the order of a few meters, comparable to the sizes of particles in Saturn's rings. Strangely, the Uranian rings seem to contain very few millimeter- and centimeter-size particles, in great contrast with the situation at Saturn. Knowing the sizes of the particles and assuming that their density is about that of the most primitive meteoroids—1.5 grams per cubic centimeter—one obtains a mass density of several hundred grams per square centimeter for the rings in general. That is considerably larger than the mass density of even Saturn's imposing *B* ring.

Unfortunately the estimated density conflicts with the density predicted from theories of the dynamical behavior of the rings. Because Uranus is not perfectly spherical, the particles in the elliptical rings undergo precession, or slew around, so that the point of closest approach (the periapsis) to Uranus advances slowly in the orbital direction. Since the rate of precession varies with the distance of the orbit from the planet, the observed nested alignment of particle orbits should be destroyed by interparticle collisions in 100 years or so, causing the orbits to become circular. The most popular theory before *Voyager 2* was that the nested ellipses are preserved because the self-gravity of the particles themselves exactly counteracts the differential precession. According to these predictions, however, the required mass density of the rings should be more than an order of magnitude smaller than the observed density.

One alternative possibility is that the slight friction produced by variations in the orbital velocity of the gently colliding particles as their orbits fall out of phase may provide the force needed to prevent further disruption. The nature of the forces that sustain the nested elliptical orbits remains elusive.

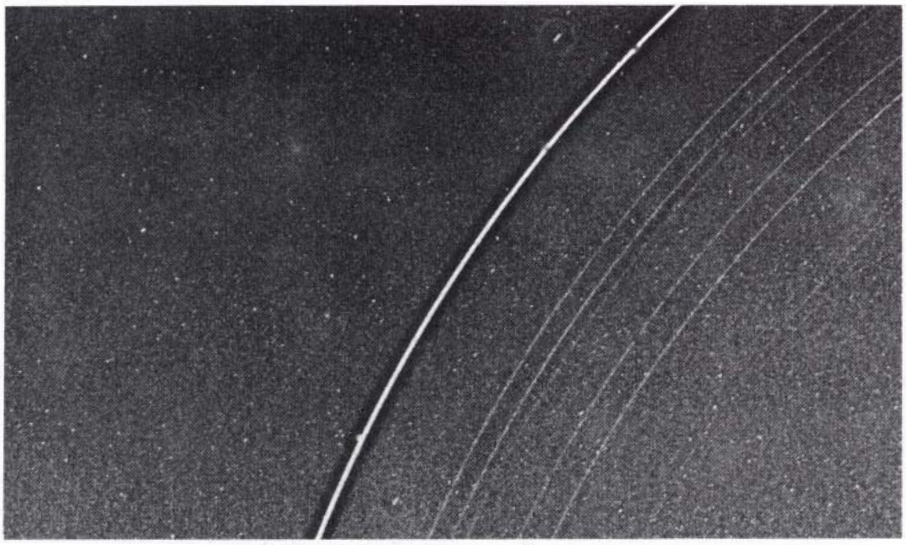
The darkness and the lack of color of the ring particles are similar to those of the 10 inner, small moons discovered by *Voyager 2*. One face of the outer, large moon of Saturn (Iapetus) appears similarly dark, but it has a reddish hue. Most asteroids, as well as the moons and rings of Jupiter, are also reddish.

Why are the inner moons and rings so dark? According to one hypothesis, their surfaces initially incorporated methane-rich ice. Energetic electrons in the surrounding radiation belts of Uranus struck the surfaces and expelled hydrogen atoms, leaving a dark carbon residue behind. (The five main moons of Uranus, which lie mostly outside the Uranian radiation belts, are considerably brighter than the rings or inner moons.) One problem with this scenario is that the radiation process, which has been modeled in terrestrial laboratories, usually produces reddening as well as darkening. Yet none of the rings or moons of Uranus is noticeably reddened.

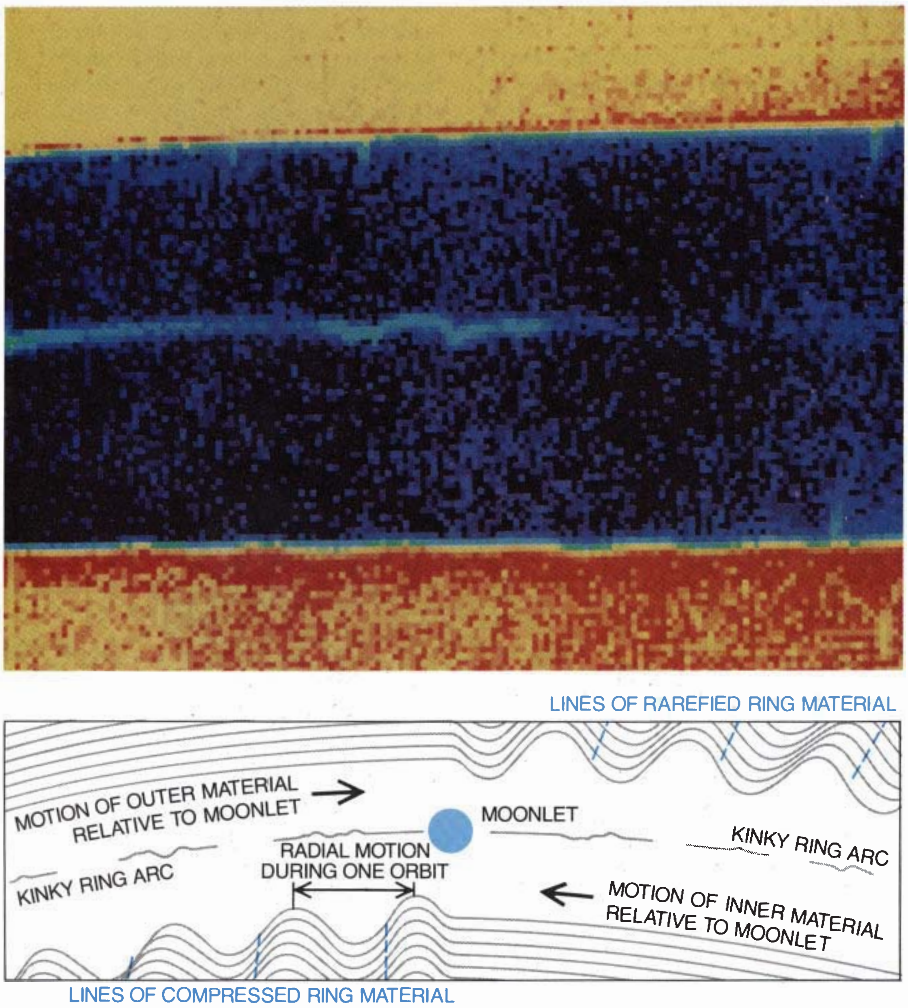
Alternatively the general darkness and lack of color in the ring and inner-moon system may attest to the presence of unaltered material with the properties of primitive meteoroids, called carbonaceous chondrites, which contain large amounts of carbon, opaque minerals and dark organic materials. A more speculative possibility is that the material may be a conglomerate, made up of atmospheric material that was thoroughly processed during an impact on Uranus of a body as large as the earth. Such an impact could also account for the fact that the pole of Uranus' rotation lies virtually in the planet's orbital plane [see "Uranus," by Andrew P. Ingersoll; SCIENTIFIC AMERICAN, January]. We look forward to comparing the Uranian ring properties with the brightness and color of the ring arcs and possible inner moons of Neptune, Uranus' sister planet, when *Voyager 2* encounters that planet in August, 1989.

Regardless of why the particles are dark, the structure of the rings must be strongly influenced by the moons of Uranus. Peter Goldreich and Scott D. Tremaine of the California Institute of Technology have proposed that the unusual narrowness and ellipticity of the rings arise from moons that confine the ring particles much as shepherds confine their flock. The essence of the proposed process is that initially circular orbits are perturbed into ellipses by gravitational tugs from passing (or overtaken) ring moons, or shepherds. By changing the eccentricity the shepherds change the angular momentum of the ring particles without changing their orbital energy. An eccentric orbit has more energy than a circular one of the same angular momentum. As excess energy is removed (for instance during subsequent collisions between particles) a circular orbit again results. The new circular orbit has a different angular momentum that places it farther from the moon.

As a consequence ring material recedes from, or seems to be repelled by, a ring moon over many cycles. The balance between the rate at which energy decays and the rate at which angular momentum is transferred through the ring may be responsible



SHEPHERDING MOONS on each side of the epsilon ring keep the ring particles in place by exerting gravitational forces on them. The moons, which appear as bright streaks, are designated 1986U8 (*outside the epsilon ring at top*) and 1986U7 (*inside the epsilon ring at bottom*). The dark band around the epsilon ring is an artifact of the data processing. *Voyager 2* did not detect shepherding moons near any of the other eight rings.



INDIRECT EVIDENCE indicates that unseen shepherding moons orbit in a 325-kilometer gap (*top*) in Saturn's rings called Encke's division. First, the inner (bottom), greenish edge has a wavy appearance compared with the outer (top) edge. Second, there are slanted intensity contours seen within the ring material at the bottom; the contours result from periodic compressions and rarefactions of ring material caused by the wavy edge. Third, there is a narrow, kinky ring arc in the center of the gap. The illustration at the bottom shows how compression and rarefaction arise, as seen from a shepherding moon.

for the overall eccentricity of these narrow shepherded rings.

It is known, for instance, that at least one gap in Saturn's rings, Encke's division, is cleared by an as yet unseen orbiting ring moon that is thought to have a radius of about 10 kilometers. The ring moon clears the gap by the same process of angular-momentum redistribution that causes the ring confinement described above. The small orbital eccentricities that transfer the momentum produce waves that are seen to form and then die out along the edges of the gap.

From the numerous high-resolution images obtained by *Voyager 2* it is clear that most of the 10 new moons lie just outside the main rings. The two innermost moons, 1986U7 and 1986U8 (which have been named Cordelia and Ophelia) straddle the epsilon (outermost) ring. Their diameters, between about 40 and 50 kilometers, are comparable to those of typical asteroids, and their orbital periods have been determined with good accuracy from *Voyager 2* image sequences.

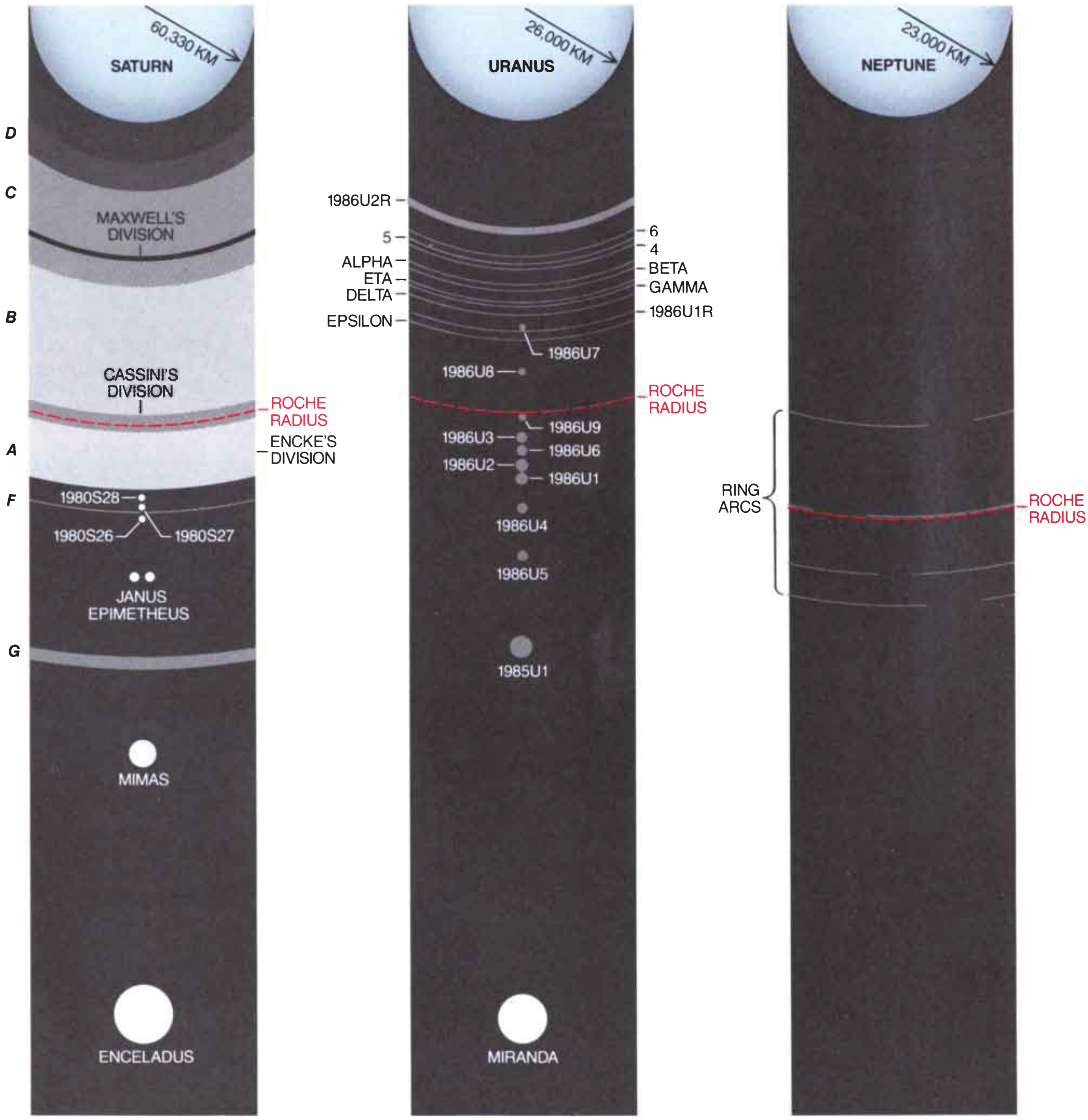
On the basis of such data, Carolyn C. Porco of the University of Arizona and Goldreich have shown that 1986U7 and 1986U8 exert "resonant" gravitational forces that keep the epsilon ring particles in their confined orbits. In a resonance relationship the gravitational tugs of the moon on the particles are timed so that they add constructively, and the orbital eccentricity will increase just as the amplitude of a swing increases if the swing is given pushes at precisely the right frequency. A resonance relationship exists between the outer edge of Saturn's *A* ring and the large moon Janus, for example; the ring particles complete seven orbits for every six orbits made by the moon. A resonance relationship also exists between the outer edge of Saturn's *B* ring and the moon Mimas; the orbital period of the moon is exactly twice that of the particles.

In the case of Uranus, particles on the inner edge of the epsilon ring make 24 orbits for every 25 made by ring moon 1986U7; particles on the outer edge make 14 orbits for every 13 made by ring moon 1986U8. In other words, material in the epsilon ring appears to be confined in much the same way as the outer edge of Saturn's *A* and *B* rings are maintained by Janus and Mimas. The process is able to shepherd ring material, but only at discrete resonance locations.

Does some kind of shepherding process also confine each of the eight other main rings of Uranus? A few other weak resonances do exist, but they cannot account for the observed orbits. Moreover, the *Voyager 2* cameras did not detect any other small ring moons. Of course, this does not mean that none exist. Limitations in the observations could allow for the existence of large numbers of small moonlets sprinkled among the rings that could in principle provide the confinement needed to keep the inner rings from spreading and to supply the required orbital eccentricity.

Another confinement problem concerns the several incomplete ring arcs around Uranus discovered by *Voyager 2*. Similar partial ring arcs have recently been discovered around Neptune, and two were seen within Encke's division during the *Voyager 1* and *Voyager 2* encounters with Saturn in 1980 and 1981. Although hypotheses of the dynamical confinement of arcs have been proposed, the conditions they must satisfy are not met at either Saturn or Uranus. The existence of partial ring arcs around Saturn and Uranus remains a puzzle.

Several insights can be drawn even from our first look at the data. A band of 10 successively smaller moons lies within the five main Uranian moons, merging with the ring system at its outer edge. Any plausible model of ring dynamics predicts that the narrow, dense rings would diffuse in width and become quite transparent in



RING AND MOON SYSTEMS of Saturn (*left*), Uranus (*middle*) and Neptune (*right*) show a striking similarity: a transition from a few large moons in outer regions to many small moons just outside ring-filled inner regions. The location of the transition coincides roughly with the Roche zone, the region in which planetary tidal forces are strong enough to fragment small objects. Recent data suggest that many smaller objects are intermingled with the rings and moons. Here the radius of each planet is set equal to 1.

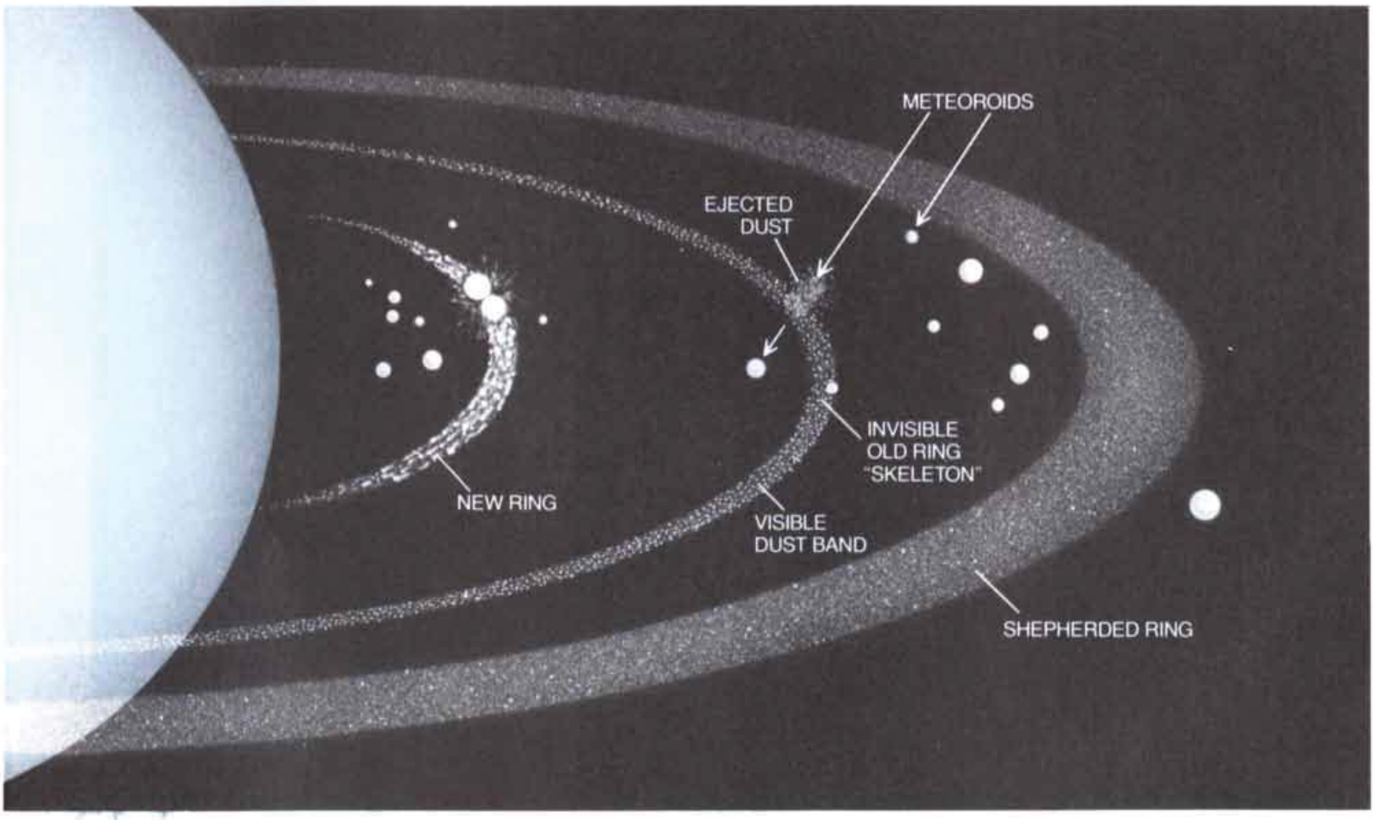
a period much shorter than the age of the solar system. As a consequence either the rings must be confined by shepherding moonlets or they must have been created recently. Incomplete ring arcs, such as those seen around Neptune and in Encke's division, have an even shorter life in the absence of some confinement process.

A number of observations suggest that the Uranian ring system, as well as other ring systems, has many other youthful features. All the small dust particles that are spread prominently, if thinly, through the ring system will be dragged out of orbit, perishing in a meteor flash within the Uranian atmosphere after only a few hundred years. Even the newly discovered moons may not have existed for more than a billion years (about a fifth of the age of the solar system). As Eugene M. Shoemaker of the U.S. Geological Survey has pointed out, any moons older than a billion years probably would have been destroyed even at the current rate of bombardment by cometary meteoroids. Uranus' inner moon Miranda, for example, has an unusual surface structure, which may attest to a geologically recent reassembly of the moon from collisional fragments. Smaller moons, which would have to be more numerous to provide the shepherding necessary to maintain the main rings, are even more susceptible to such catastrophic destruction.

It may be that some or even all of the narrow rings of Uranus were created, simultaneously or separately, during the catastrophic destruction of moons by cometary meteoroids. Most of the rings, even if the largest mass densities are assumed, contain only the mass of a one- or two-kilometer-radius object. The earliest precursors of the rings may have gone long ago, swept up by surviving ring moons or dragged into the planet itself. Similarly, the partial arcs seen by *Voyager 2* may be transient clumps of debris released during impacts involving smaller and as yet undetected members of a band of moonlets that resembles an asteroid belt. As such partial arcs spread they would become symmetrical, nearly transparent bands of debris. Even if the large-particle skeletons of such bands could not be seen, their continual erosion by micrometeoroids would provide a source for the observed bands of microscopic dust. Similar processes could be taking place in the ring and moon systems of Jupiter, Saturn and Neptune.

The underlying population of objects that could be ultimately responsible for such interactions might consist of literally thousands or even millions of moonlets whose sizes range from hundreds of meters to a few kilometers. The moonlets could be the extension of the inward trend toward more numerous, smaller moons seen in all three giant planet systems that *Voyager 2* has explored. A population of moonlets would provide a missing link between rings and major satellites. It might be no accident to find such a population near the so-called Roche zone: the region in which a planet's tidal forces prevent the growth of large satellites.

In all, we are beginning to suspect that the austere Uranian ring system may have had a violent and chaotic past. Uranus' present system—consisting of 10 narrow rings, numerous dusty bands, some narrow ring arcs and a bevy of moonlets—may be only a fragment of its former self and merely one more passing stage in an ongoing process of creation and loss from which future rings of Uranus will arise. The ring systems of Jupiter, Saturn and Neptune may have had a similar history. Indeed, some aspects of ring and moon systems may be as evanescent, and continually evolving, as the drifting continents on the earth are now known to be.



FORMATION OF RINGS and partial ring arcs may have taken place as moonlets collided with one another or were eroded or destroyed by incoming meteoroids. The collisions would have generated lumps of material; small differences in the velocity of the material would have caused it to spread rapidly into arcs. After a longer time each arc could have become a complete, if nearly transparent, ring (*left*). Such stable bands could then provide a source of target material that would be eroded by microscopic meteoroids, continuously generating short-lived dust (*middle*). Some rings could, of course, be sustained by shepherding moons (*right*).