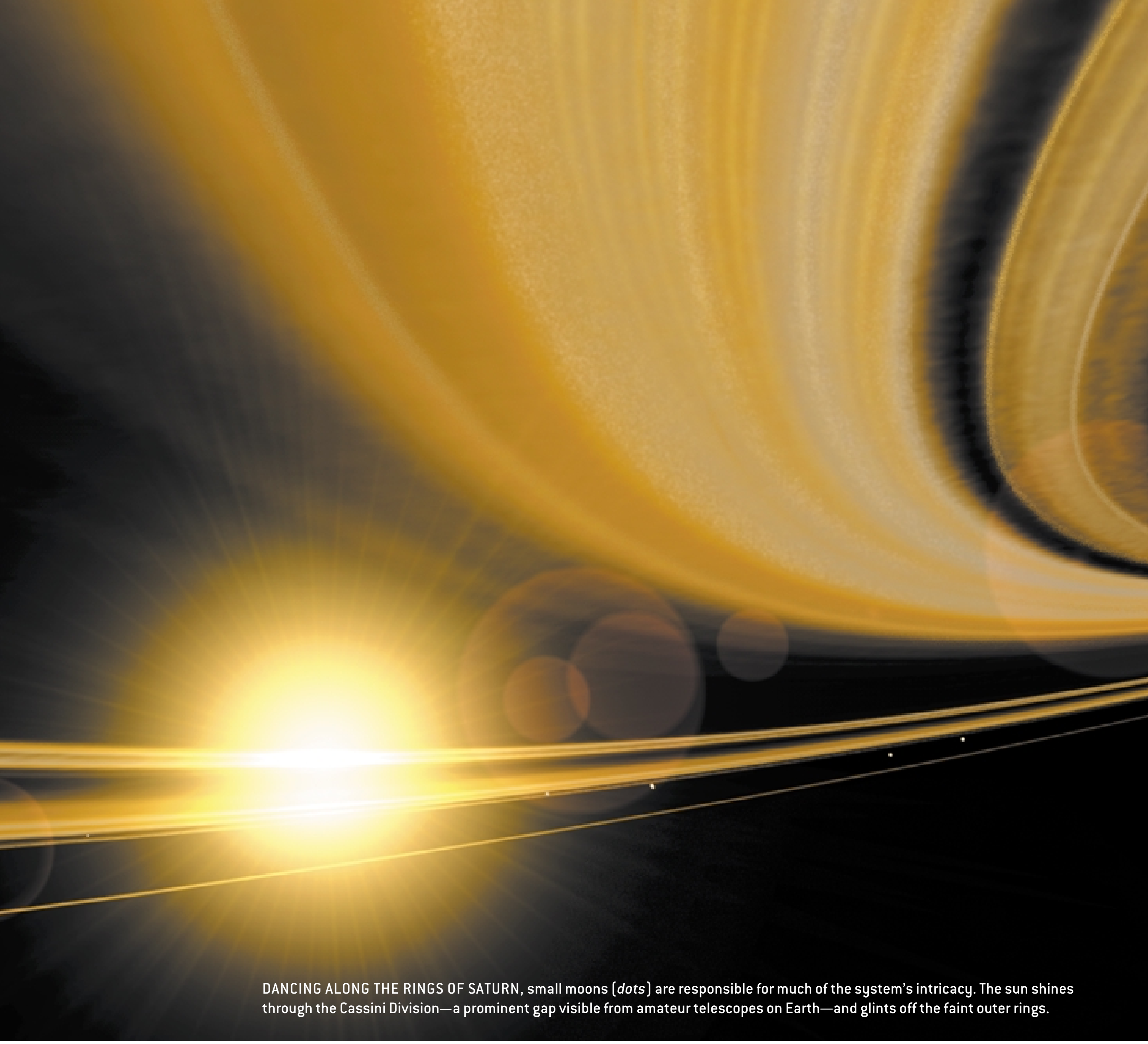
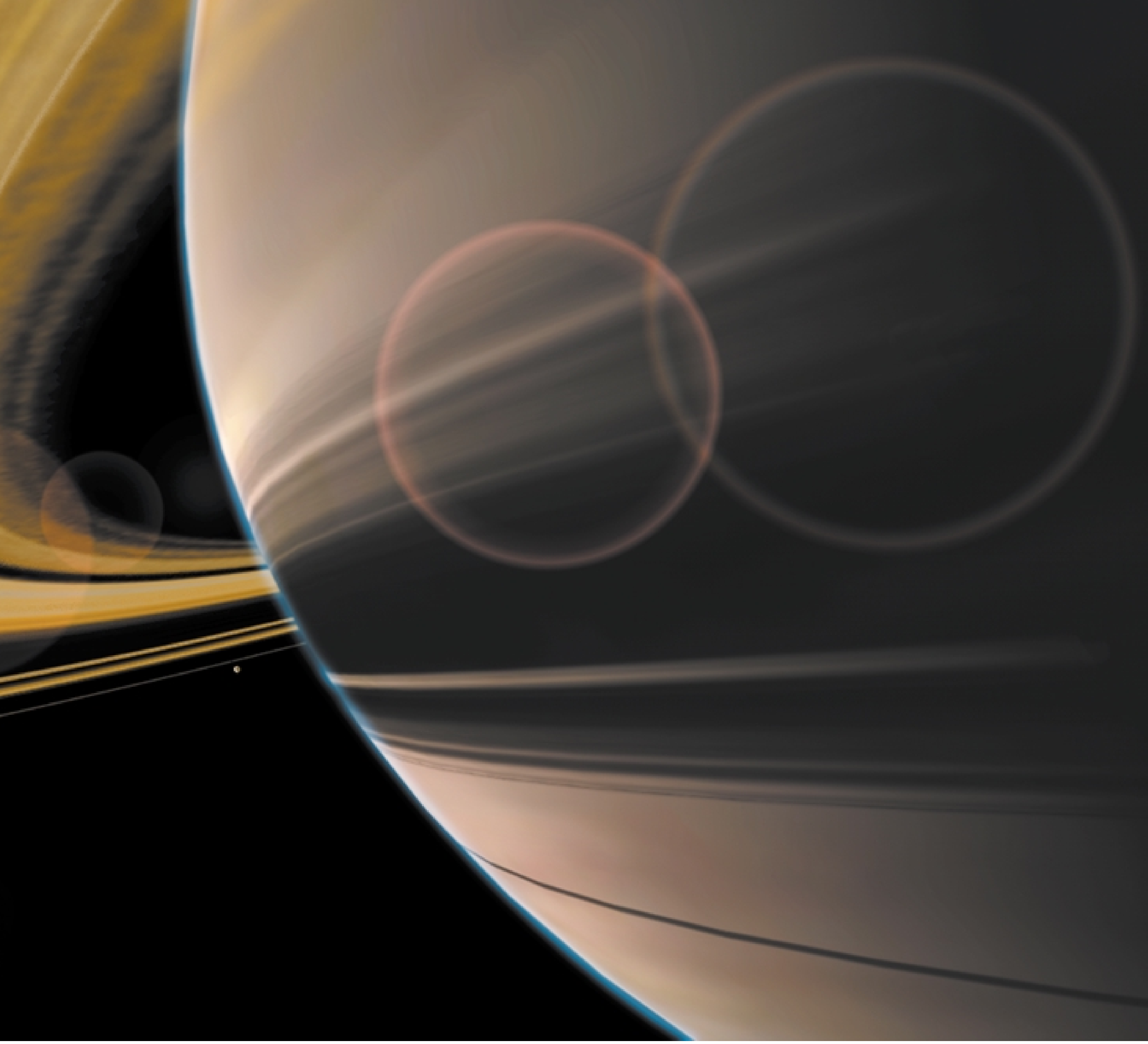


DANCING ALONG THE RINGS OF SATURN, small moons (*dots*) are responsible for much of the system's intricacy. The sun shines through the Cassini Division—a prominent gap visible from amateur telescopes on Earth—and glints off the faint outer rings.

Bejeweled

By Joseph A. Burns, Douglas P. Hamilton and Mark R. Showalter



Worlds

What an impoverished universe it would be if Saturn and the other giant planets lacked rings. Planetary scientists are finally working out how gravity has sculpted these elegant ornaments

Much of the modern world's economy is based on inventions made possible by 19th-century physicist James Clerk Maxwell, father of electromagnetism and pioneer of thermodynamics. In terms of raw economic benefit, though, not much can be said for another of Maxwell's favorite subjects: the rings of Saturn. Apart from inspiring the sales of executive desk toys, planetary rings do not contribute conspicuously to the material wealth of nations. And yet that does not blunt their appeal. In his 1857 Adams Prize essay, Maxwell wrote:

> There are some questions in Astronomy to which we are attracted … on account of their peculiarity … [rather] than from any direct advantage which their solution would afford to mankind…. I am not aware that any practical use has been made of Saturn's Rings … [b]ut when we contemplate the Rings from a purely scientific point of view, they become the most remarkable bodies in the heavens, except, perhaps, those still less *useful* bodies—the spiral [galaxies]…. When we have actually seen that great arch swung over the equator of the planet without any visible connection, we cannot bring our minds to rest.

A century and a half later Saturn's rings remain a symbol of all that is exotic and wondrous about the universe. Better observations have only heightened their allure. The findings of the past two decades have so overturned previous knowledge that essentially a new ring system—one much more complex and interesting than theory, observation or imagination had suggested—has been revealed.

Other giant planets besides Saturn have rings, and no two systems look alike. Rings are strange, even by the standards of astronomy. They are sculpted by processes that can be feeble and counterintuitive. For example, in rings, gravity can effectively repel material. We now appreciate that rings, once thought to be static, are continually evolving. We have seen the vital symbiosis between satellites and rings. Most important, we have recognized that planetary rings are more than just exquisite phenomena. Like Maxwell, modern scientists see analogies between rings and galaxies; in a very fundamental way, rings may also afford a glimpse into the solar system's ancient beginnings.

Saturn's rings, initially spied in 1610 by Galileo Galilei and interpreted as a planet-encircling hoop five decades later by Christiaan Huygens, stood alone for more than three and a half centuries. Then, in a span of just seven years, rings were discovered around the other three giant planets. Uranus's were detected first, in 1977. James L. Elliot, then at Cornell University, monitoring a star's brightness as Uranus crossed in front of it, noticed the signal blinking on and off. He inferred that a series of narrow bands, slightly elliptical or inclined, circumscribe the planet [see "The Rings of Uranus," by Jeffrey N. Cuzzi and Larry W. Esposito; SCIENTIFIC AMERICAN, July 1987]. In 1979 the Voyager 1 spacecraft sighted Jupiter's diaphanous rings. Finally, in 1984, a technique like Elliot's detected pieces of rings—but not full rings—around Neptune.

Those heady days passed, and ring research stagnated until the mid-1990s. Since then, a new era of ring exploration has begun. Observations have poured in from the Hubble Space Telescope, ground-based telescopes and the Galileo probe in orbit about Jupiter [see "The Galileo Mission to Jupiter and Its Moons," by Torrence V. Johnson; SCIENTIFIC AMERICAN, February 2000]. Saturn's faintest rings and satellites became visible in 1995 and 1996, when the positions of Earth and Saturn made the system appear edge-on, thereby reducing the glare from the main rings. And in July 2004 the Cassini spacecraft will begin its four-year tour of the Saturnian system.

Four-Ring Circus

ALTHOUGH THE FOUR known ring systems differ in detail, they share many general attributes. They are all richly textured, made up of multiple concentric rings often separated by gaps of various widths. Each ring is composed of innumerable par-

THE AUTHORS

JOSEPH A. BURNS, DOUGLAS P. HAMILTON and *MARK R. SHOWALTER* started working together at Cornell University, where Burns is a professor and Hamilton and Showalter were graduate students. Burns studied naval architecture in college but then got caught up in the excitement of the space age and changed fields. He is now I. P. Church Professor of Engineering and Astronomy. Hamilton, a professor at the University of Maryland, received the 1999 Urey Prize of the American Astronomical Society for his studies of the celestial mechanics of dust. Showalter is a researcher at Stanford University, where he oversees NASA's archive of planetary ring data. All three authors are deeply involved in space missions to the outer planets.

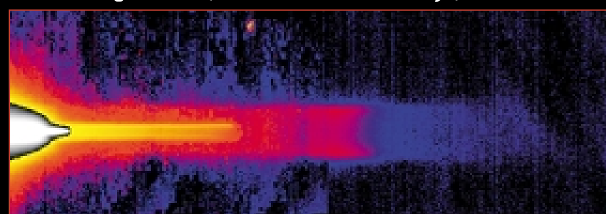
Jupiter

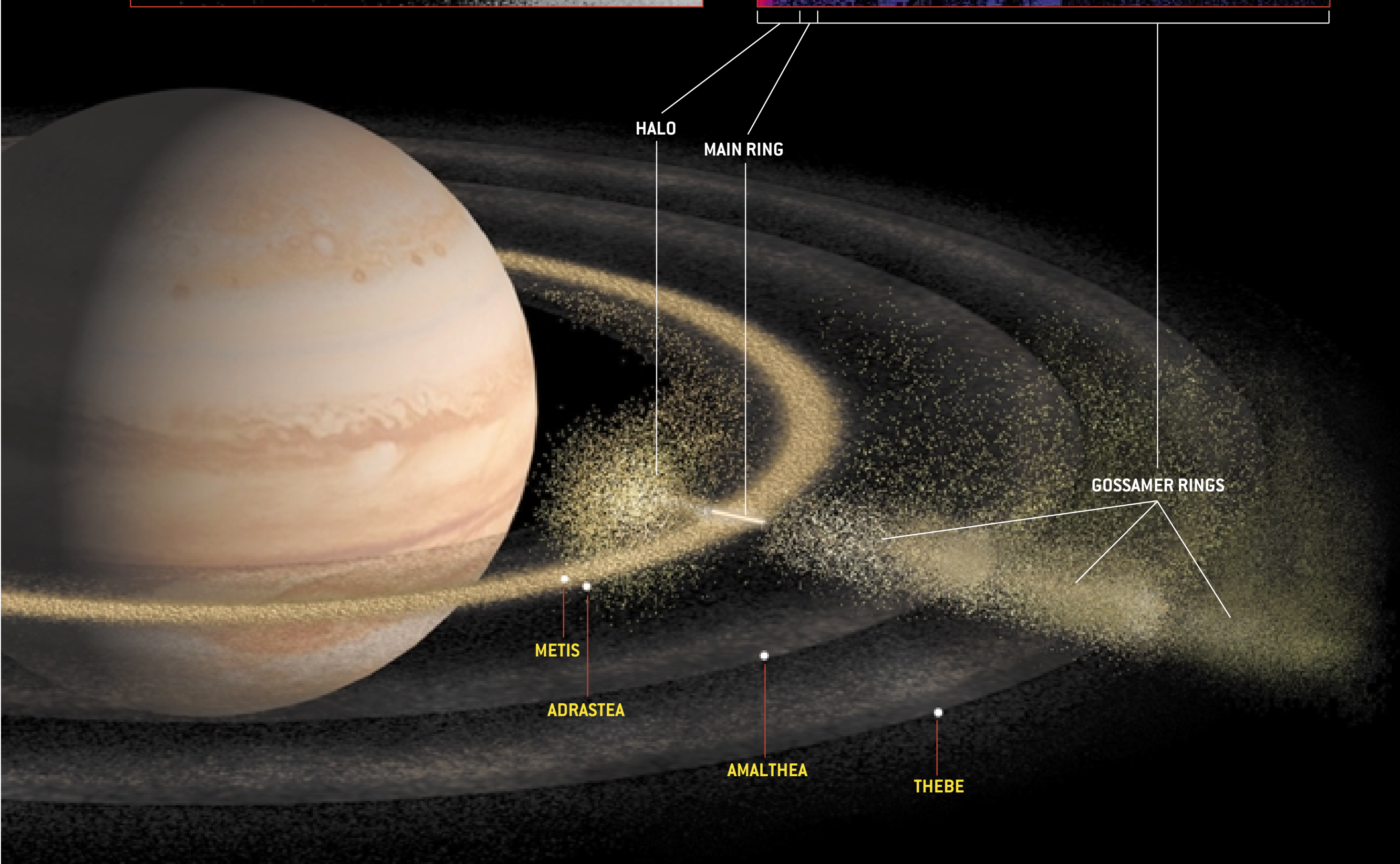
The largest planet in the solar system has rings of puzzling subtlety. They are composed of finer particles and are less flattened than the rings around other planets.

This mosaic by the Galileo spacecraft shows Jupiter in eclipse, highlighting its upper atmosphere and rings.

A tenuous, puffy halo rises up from the main ring's inner edge.

Faint gossamer rings (*yellow, red and blue bands*) extend beyond the main ring and halo (*black-and-white blob at left*).

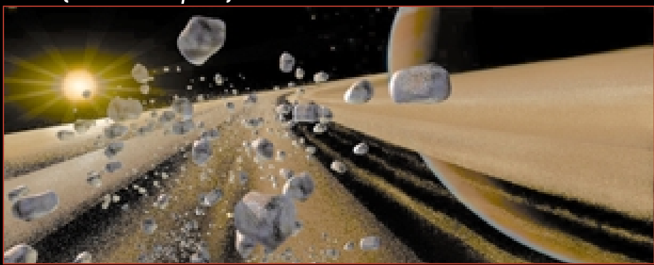




Saturn

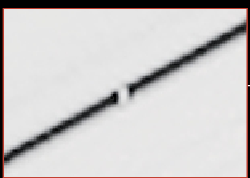
Saturn's rings, the most baroque, seem to get more complicated the closer scientists look. The famous Voyager images may pale in comparison to what the Cassini spacecraft finds in 2004.

A RING (*artist's conception*)



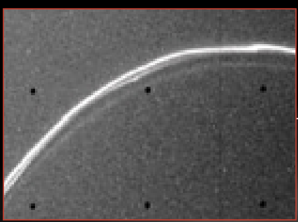
In at least one place, the meter-size snowballs are cleared away by satellites.

ENCKE GAP



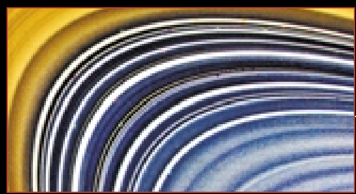
Pried open by the tiny satellite Pan.

F RING



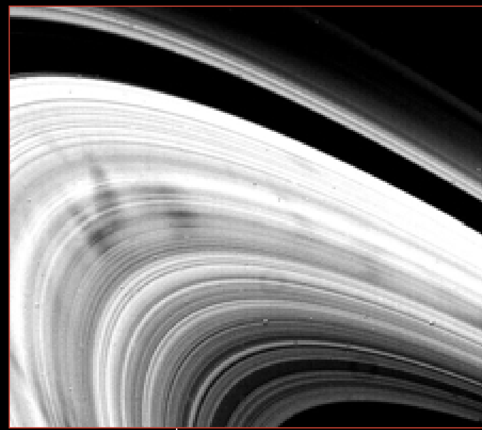
The multiple strands are knotted by the tugs of two nearby satellites.

C RING

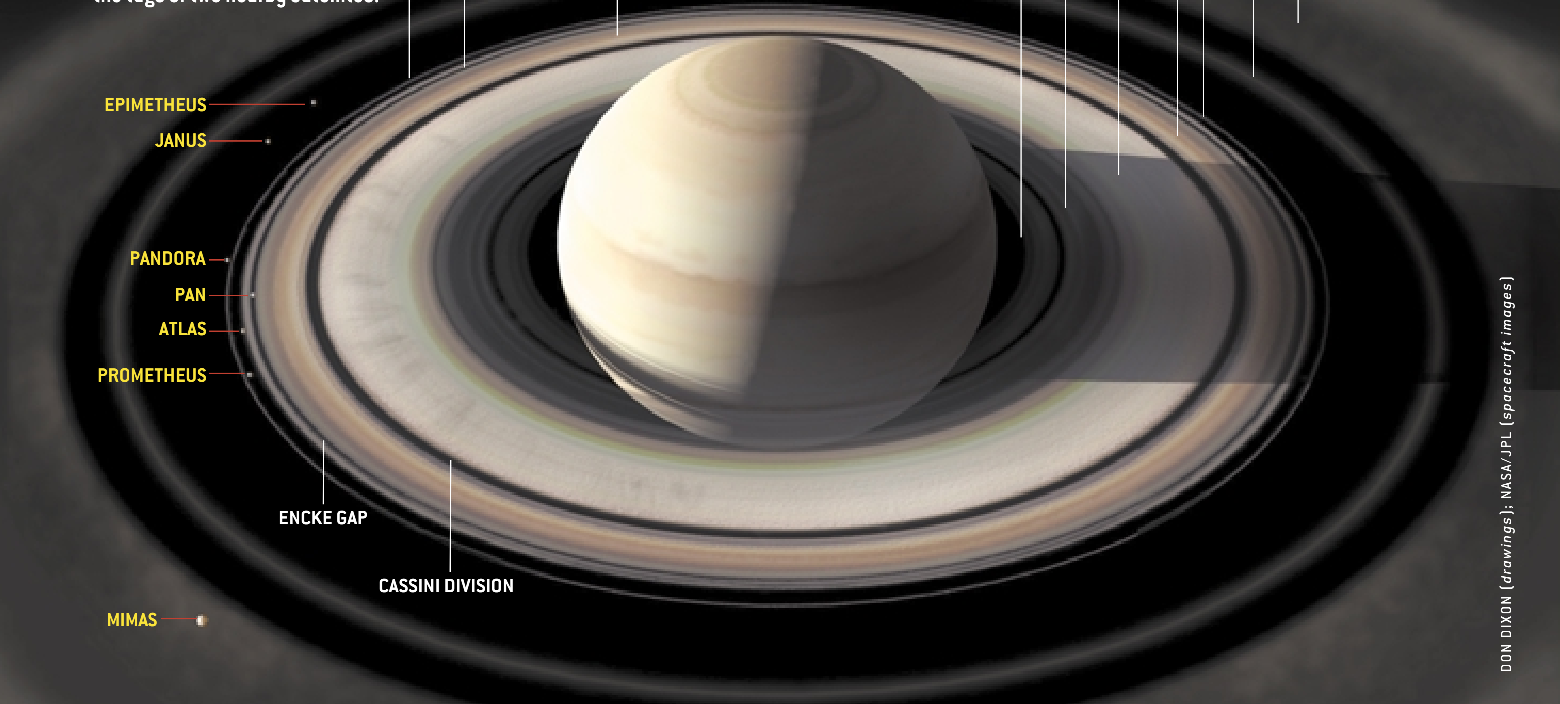


This image exaggerates the slight color differences between the C ring (*blue*) and B ring (*gold*).

B RING



The "spokes" are fleeting smudges made of levitating dust grains. The innumerable ringlets remain unexplained.



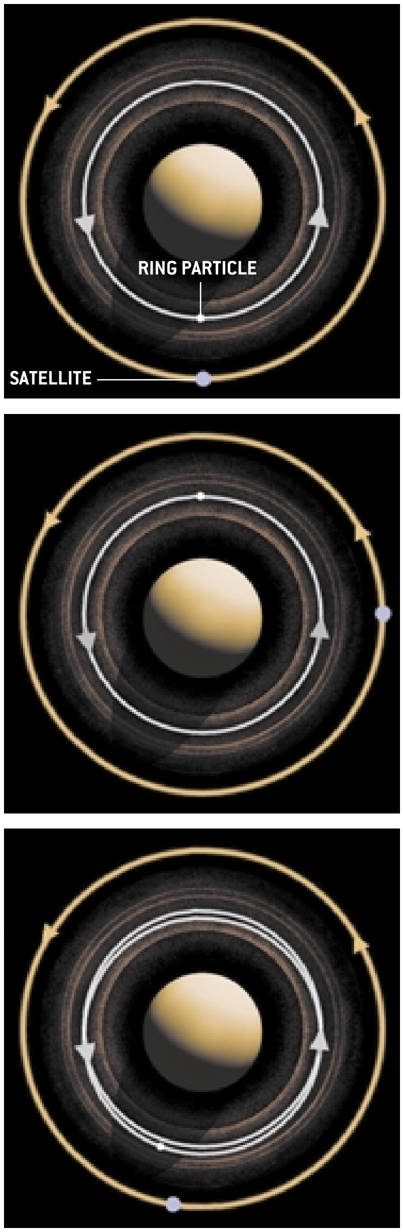
DON DIXON (*drawings*); NASA/JPL (*spacecraft images*) ticles—chunks of rock and ice—that independently circle the central planet while gently jostling one another. Rings fall into two general categories based on how densely packed the particles are, as described by the optical depth, a measure of the exponential decay of light as it penetrates perpendicularly through the ring. For the densest rings, such as Saturn's main rings (designated A and B) and the Uranian rings (designated by numbers and Greek letters), the optical depth can be as high as 4, which means that a mere 2 percent of the light leaks through. The most tightly packed of these rings contain particles that range from a few centimeters to several meters in diameter.

Particles in a dense ring system collide frequently, often several times during each orbit around the planet. In the process, energy is lost and angular momentum is redistributed. Because particles nearer to the planet move at a higher speed than do particles farther out, collisions hold back the inner particles (which then fall toward the planet) and push forward the outer ones (which then move away from the planet). Thus, a ring tends to spread radially. But the spreading takes time, and in this regard, a ring may be thought of as a viscous fluid that slowly diffuses inward and outward. Saturn's rings have an effective kinematic viscosity like that of air.

The energy loss, combined with angular-momentum redistribution, causes a dense ring system to flatten. Whatever its initial shape, the system quickly becomes a thin, near-equatorial disk. Saturn's rings are only tens of meters from top to bottom even though they stretch across several hundred thousand kilometers; they are proportionally as thick as a sheet of tissue paper spread over a football field. A similar effect flattens the debris disks around stars and the gaseous disks of spiral galaxies.

Another consequence of dense packing is to strengthen the particles' own mutual gravitational attraction. This may be why Uranus's rings are slightly out of round: their self-gravity resists the tendency to smear into a circular band.

At the other extreme, the faintest known rings, such as Jupiter's rings and Saturn's outermost rings, have optical depths between 10^{-8} and 10^{-6}. Particles are as spread out as baseball outfielders. Because they collide infrequently, they tend not to settle into a flat disk. As we know from how these rings scatter light, the particles are fine dust, typically microns in size, comparable to the size of smoke particles. So these structures are literally smoke rings. The particles display unusual dynamics because, being so small, they are significantly affected by electromagnetic and radiation forces in addition to gravity.



RESONANCE between a satellite and a ring particle means that their two orbits are choreographed: in this case, the particle goes around exactly twice in the time it takes the satellite to trundle around once. Because the bodies always encounter each other at the same position, gravitational tugs can add up.

DON DIXON

Neptune's rings do not fall into this neat dichotomy; their optical depth lies between the two extremes. The Neptunian system is anomalous in other respects as well. Its densest ring is not a smooth band; it contains discontinuous arcs that together encompass less than a tenth of the circumference. Without some confinement mechanism at work, these structures should spread fully around the planet in about a year. Yet recent Hubble images and ground-based observations find that the positions of the arcs have shifted little in the past 15 years.

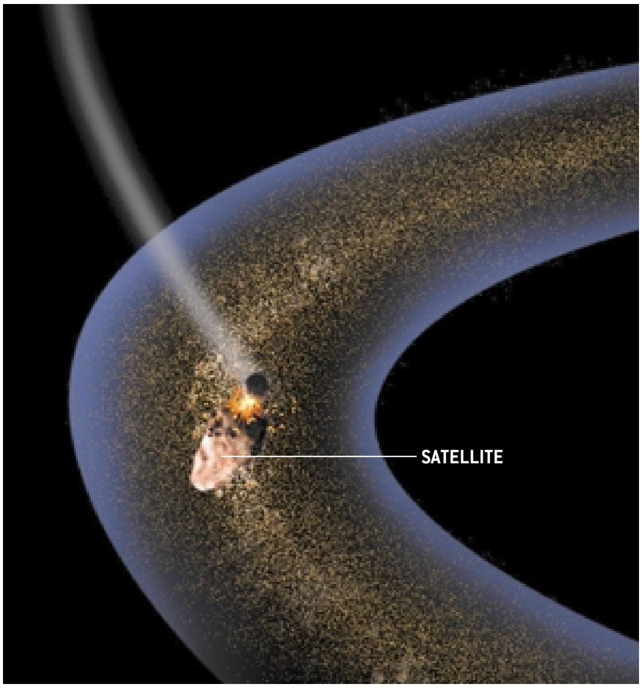
Lords of the Rings

ALL DENSE RING systems nestle close to their planets, extending no farther than the so-called Roche limit, the radius within which the planet's tidal forces overwhelm the tendency of ring particles to agglomerate into larger bodies. Just outside the Roche limit is a zone where small, irregularly shaped moons can coexist with the rings. The interactions between rings and ring moons are implicated in many of the strangest aspects of rings.

For example, Saturn's E ring reaches across a broad region that encompasses the satellites Mimas, Tethys, Dione and Rhea, peaking in brightness at the orbit of the smooth, icy moon Enceladus. The narrow F ring, a tangle of several lumpy strands, sits isolated just beyond Saturn's A ring and also is straddled by two moons, Pandora and Prometheus. Correlations of satellite positions and ring features occur in the Jovian, Uranian and Neptunian systems as well.

Explaining how satellites wield such power has been the major advance in ring science over the past two decades. Three basic processes appear to be at work. The first is the orbital resonance, a tendency of gravitational forces to be magnified at positions where a particle's orbital period matches an integer ratio (say, $m:n$) of a satellite's orbital period. For instance, a particle at the outer edge of Saturn's B ring is in a 2:1 resonance with Mimas, meaning that it goes around the planet precisely twice for each lap the satellite completes. In another example, the exterior boundary of Saturn's A ring is in a 7:6 resonance with the satellites Janus and Epimetheus.

Orbits that lie near resonant locations suffer unusually large distortions because the gentle tugs of moons are repeated systematically and therefore build up over time. Resonances are stronger for particles in orbits near a moon, but when the orbits are too close, different resonances vie for control, and motions become chaotic. Resonances are strongest when $m = n + 1$ (for example, 2:1 or 43:42) and weaken rapidly as m and n differ more and more. Throughout Saturn's enormous rings, only a few dozen ring locations respond to strong satellite resonances.



IF SOMETHING SLAMS into a satellite, material flies off and becomes part of a ring. Conversely, the satellite steadily sweeps up material. The balance of these competing effects determines the size of faint rings.

The outcome of these resonant perturbations varies. Strong ones clear material, accounting for the outer edges of Saturn's A and B rings. In some places, gaps are opened. Such a resonance may account for Neptune's discontinuous ring. Analogous resonances explain the distribution of material in the asteroid belt, for which the sun plays the role of the planet and Jupiter plays the role of the satellite.

Elsewhere in the A ring, resonances generate waves. If the satellite has an elliptical orbit, the result is a spiral wave, a miniature version of the pinwheel pattern of our galaxy. If the satellite has a tilted orbit, the result is a series of vertical bending waves, an out-of-plane corrugation—small ripples in a cosmic carpet.

Although resonances typically involve satellites, any force that repeats periodically at an integer ratio of the orbital period—such as lumpy planetary gravitational fields or variable electromagnetic forces—will be similarly effective. The Jovian system has become infamous for such resonances. Inward of a radius of 120,000 kilometers, the ring abruptly puffs up from a flat disk to a thick torus. A ring particle at that radius orbits three times for every two planetary spins; thus, the planet's tilted magnetic field pushes it ever upward. Still closer to the planet, at a radius of 100,000 kilometers, the brightness of the Jovian ring drops sharply. That happens to be the location of the 2:1 electromagnetic resonance. Particles that drift to this position are spread so thinly that they vanish against the giant planet's glare.

The second basic way that satellites govern ring structures is by influencing the paths of ring particles. The gravitational interaction of a satellite and a nearby particle is somewhat counterintuitive. If these two bodies were isolated in deep space, their close encounters would be symmetrical in space and time. The particle would approach the satellite, accelerate, zip around, emerge on the other side and decelerate (assuming it did not collide). The departure leg would be the mirror image of the inbound path (a hyperbola or parabola). Although the particle would have changed direction, it would eventually return to its original speed.

Ringmaster

IN A RING SYSTEM, however, a satellite and particle are not isolated—they are in orbit around a third object, the planet. Whichever body is nearer to the planet orbits faster. Suppose it is the particle. During the close encounter, the gravity of the satellite nudges the particle into a new orbit. The event is asymmetrical: the particle moves closer to the satellite, and the gravitational interaction of the two bodies strengthens. So the particle is unable to regain the velocity it once had; its orbital energy and angular momentum have decreased. Technically, that means its orbit is distorted from a circle to an ellipse of slightly smaller size; later, collisions within the ring will restore the orbit to a circle, albeit a shrunken one.

The net effect is that the particle is pushed inward. Its loss is the satellite's gain, although because the satellite is more massive, it moves proportionately less. If the positions are reversed, so are the roles: with the satellite on the inside, the particle will be pushed outward and the satellite inward. In both cases, the attractive gravity of a satellite appears to *repulse* ring material. None of Newton's laws have been broken; this bizarre outcome occurs when two bodies in orbit around a third interact and lose energy. (It is completely different from the "repulsive" gravity that occurs in theories of the expanding universe.)

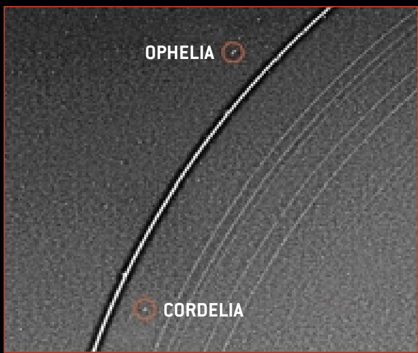
Like resonances, this mechanism can pry open gaps in rings. The gaps will grow until the satellite's repulsive forces are counterbalanced by the tendency of rings to spread during collisions. Such gaps are present within Saturn's A, C and D rings, as well as throughout the Cassini division, a zone that separates the A and B rings.

Conversely, the process can squeeze a narrow ring. Satellites on either side of a strand of material can shepherd that material, pushing back any particles that try to escape. In 1978 Peter Goldreich and Scott D. Tremaine, then both at the California Institute of Technology, hypothesized the shepherding process to explain the otherwise puzzling stability of the threadlike rings of Uranus [see "Rings in the Solar System," by James B. Pollack and Jeffrey N. Cuzzi; SCIENTIFIC AMERICAN, November 1981]. The satellites Cordelia and Ophelia keep Uranus's ε ring corralled. Saturn's F ring appears to be herded by Prometheus and Pandora. To be sure, most of the visible gaps and narrow

DON DIXON

Uranus

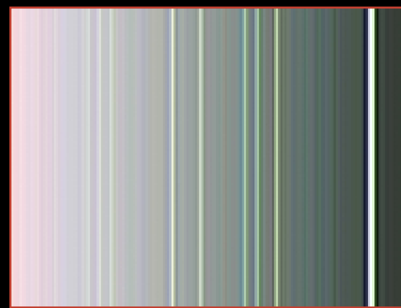
What makes the rings of Uranus so odd is that most of them are slightly elliptical and tilted. Somehow they have resisted the forces that would have circularized and flattened them.

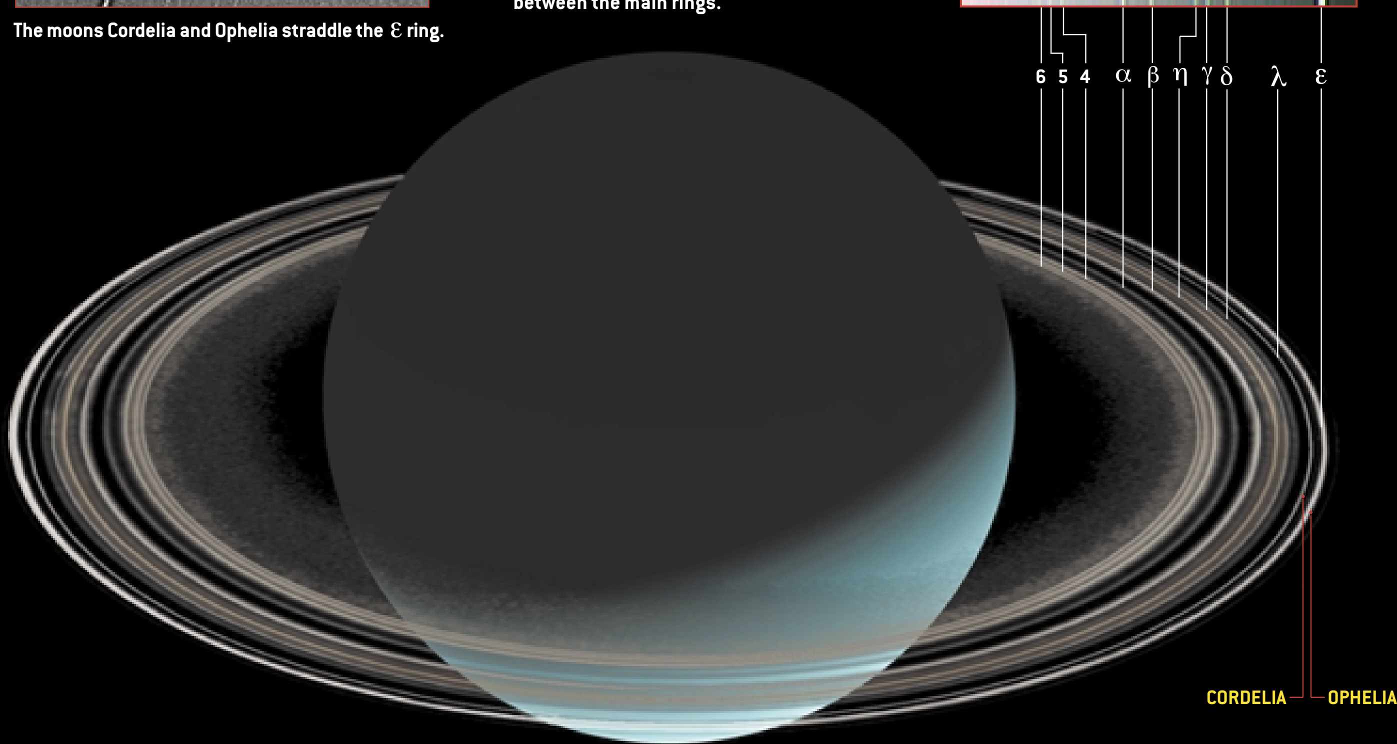


The moons Cordelia and Ophelia straddle the ε ring.

Using a different viewing angle and longer exposure, Voyager saw dust between the main rings.

This false-color image hints at differing particle properties. The dusty λ ring is too faint to see here.





ringlets remain unexplained. Perhaps they are manipulated by moons too small to see with present technology. The Cassini orbiter may be able to spy some of the hidden puppeteers.

Yet another effect of repulsive gravity is to scallop ring edges. These undulations are easiest to understand from the vantage point of the satellite. In rings, a continuous stream of particles flows past the satellite. When these particles overtake the moon, gravity modifies their circular orbits into elliptical ones of almost the same size. The particles no longer maintain a constant distance from the planet. Someone riding on the satellite would say that the particles have started to weave back and forth in concert. The apparent motion is sinusoidal with a wavelength proportional to the distance between the orbits of the satellite and the particle.

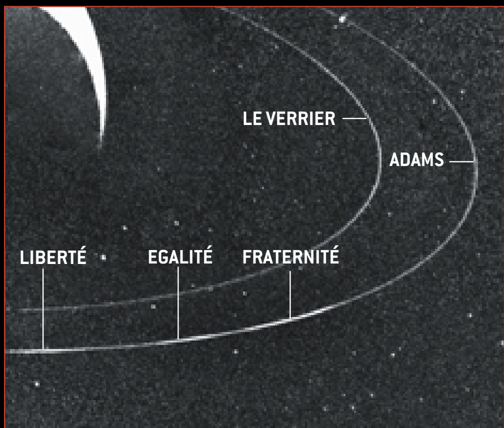
The resulting wave appears behind the satellite if the particle is on the outside and in front of the satellite if the particle is on the inside. It is akin to the wake of a boat in an unusual river where the water on one side of the boat moves faster than the boat itself. One of us (Showalter) analyzed the scalloped edges of Saturn's Encke division to pinpoint a small satellite, Pan, that had eluded observers. Another example is the F ring, whose periodic clumps seem to have been imprinted by Prometheus.

DON DIXON (*drawing*); NASA/JPL (*spacecraft images*)

Neptune

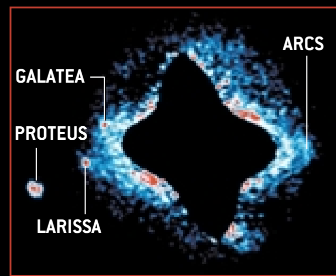
The least known and least understood rings are those of Neptune. The outer ring contains clumps—the so-called arcs. It may take another spacecraft visit to figure them out.

LE VERRIER AND ADAMS RINGS

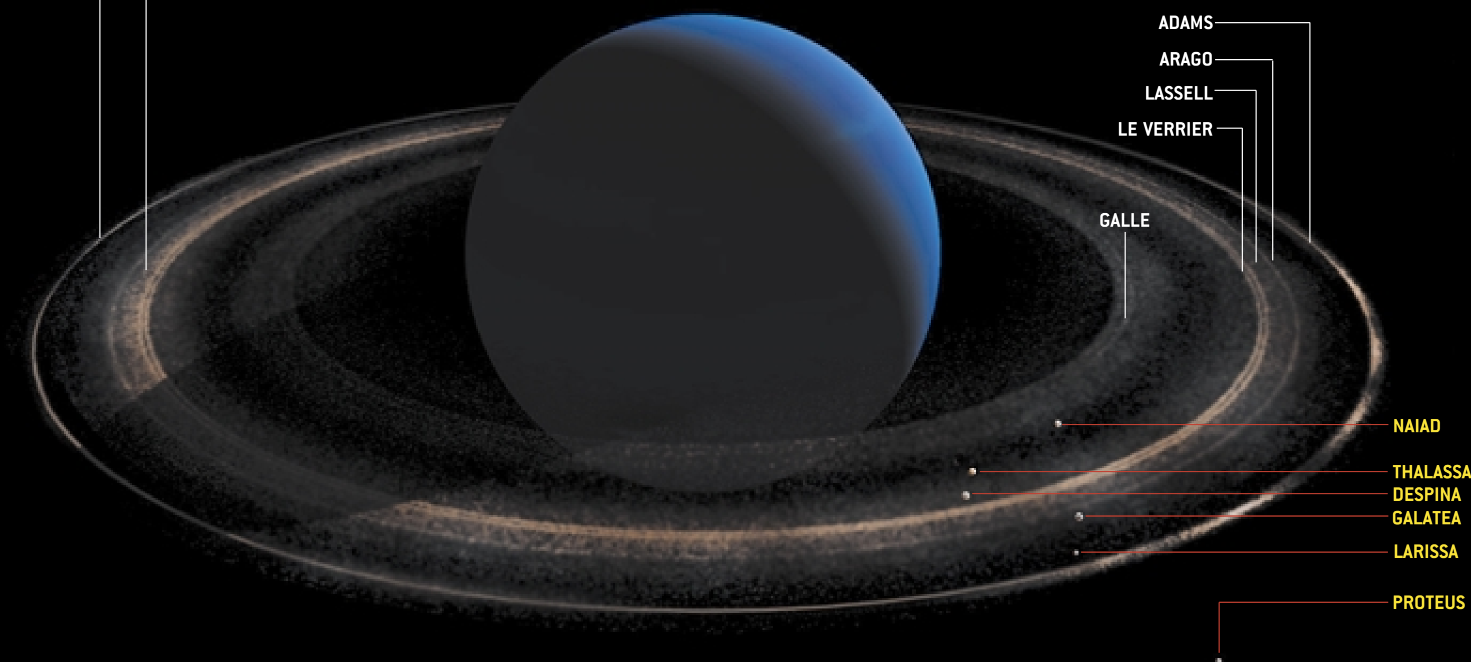


Voyager images from 1989 reveal clumps in the outermost ring, perhaps the result of a complex satellite resonance.

The ring arcs also appear in this Hubble Space Telescope image from 1998. Not only have the arcs persisted, but they have orbited slightly slower than predicted.



Ground-based observations in 1998 agree with Hubble's conclusions.



Those Dirty Rings

THE THIRD AND FINAL effect of moons on rings is to spew out and soak up material. This role, especially vital for faint, dusty rings such as those around Jupiter, has come into clear view only with the Galileo mission to Jupiter. Earlier the Voyager spacecraft had discovered Jupiter's rings as well as two small moons, Adrastea and Metis, close to the main ring's outer edge. But its camera was not sharp enough to tell us what the satellites actually did. Were they shepherds that prevented the rings' outward spread? Or were they the source of ring material that, once placed into orbit, drifted inward? Neither could Voyager make sense of a faint outer extension—a gossamer ring that accompanied the main one.

Galileo's imaging system found that the gossamer ring vanished abruptly beyond the orbit of the moon Amalthea. It discovered another, fainter gossamer ring that extended as far as the moon Thebe and no farther. On the flight home from the meeting at which these images were first available, one of us (Burns) noticed the smoking gun: the vertical extent of the innermost gossamer ring was equal to the orbital tilt of Amalthea, and the thickness of the outer gossamer ring perfectly matched the inclination of Thebe. Furthermore, both gossamer rings were brightest along their top and bottom edges, indicating a pileup of material—which is exactly what one would expect if particles and satellites shared the same orbital tilt. This tight association is most naturally explained if the particles are debris ejected by meteoroid impacts onto the satellites.

Ironically, small moons should be better sources of material than big ones: though smaller targets, they have weaker gravity, which lets more debris escape. In the Jovian system the most effective supplier is calculated to be 10 or 20 kilometers across—just about the size of Adrastea and Metis, explaining why they generate more formidable rings than do Amalthea and Thebe, which are much larger.

An odd counterexample is Saturn's 500-kilometer-wide moon, Enceladus, which appears to be the source of the E ring. Powerful impacts by ring particles, as opposed to interplanetary projectiles, might explain how Enceladus manages to be so prolific. Each grain that hits Enceladus generates multiple replacement particles, so the E ring could be self-sustaining. Elsewhere such collisions usually result in a net absorption of material from the ring.

Ring Out the Old

THE EVIDENT IMPORTANCE of sources and sinks reopens the classic question of whether rings are old and permanent or young and fleeting. The former possibility implies that rings could date to the formation of the solar system. Just as the protosun was surrounded by a flattened cloud of gas and dust out of which the planets are thought to have emerged, each of the giant planets was surrounded by its own cloud, out of which satellites emerged. Close to each planet, within the Roche limit, tidal forces prevented material from agglomerating into satellites. That material became a ring instead.

Alternatively, the rings we see today may have arisen much later. A body that strayed too close to a planet may have been torn asunder, or a satellite may have been shattered by a high-speed comet. Once a satellite is blasted apart, the fragments will reagglomerate only if they lie beyond the Roche limit. Even then, they will be unconsolidated, weak rubble piles susceptible to later disruption.

Several lines of evidence now suggest that most rings are young. First, tiny grains must lead short lives. Even if they survive interplanetary micrometeoroids and fierce magnetospheric plasma, the subtle force exerted by radiation causes their orbits to spiral inward. Unless replenished, faint rings should disappear within just a few thousand years. Second, some ring moons lie very close to the rings, even though the back reaction from spiral density waves should quickly drive them off.

Third, icy ring particles should be darkened by cometary debris, yet they are generally bright. Fourth, satellites just beyond Saturn's rings have remarkably low densities, as though they are rubble piles. Finally, some moons are embedded within rings. If rings are simply primordial material that failed to agglomerate, how did those moons get there? The moons make most sense if they are merely the largest remaining pieces of a shattered progenitor.

So it seems that rings are not quite the timeless fixtures they appear to be. Luke Dones of the Southwest Research Institute in Boulder, Colo., has suggested that Saturn's elaborate adornments are the debris of a shattered moon roughly 300 to 400 kilometers across. Whether all rings have such a violent provenance, we now know they were not simply formed and left for us to admire. They continually reinvent themselves. Joshua E. Colwell and Larry W. Esposito of the University of Colorado envision recycling of material between rings and ring moons. Satellites gradually sweep up the particles and subsequently slough them off during energetic collisions. Such an equilibrium could determine the extent of many rings. Variations in the composition, history and size of the planets and satellites would naturally account for the remarkable diversity of rings.

Indeed, the emerging synthesis explains why most of the inner planets are ringless: they lack large retinues of satellites to provide ring material. Earth's moon is too big, and any micron-size dust that does escape its surface is usually stripped away by solar gravitational and radiation forces. Mars, with its two tiny satellites, probably does have rings. But two of us (Hamilton and Showalter) were unable to find any rings or smaller satellites in Hubble observations last year. If a Martian ring does exist, it must be exceedingly tenuous, with an optical depth of less than 10^{-8}.

As often happens in science, the same basic principles apply to phenomena that at first seem utterly unrelated. The solar system and other planetary systems can be viewed as giant, star-encircling rings. Astronomers have seen hints of gaps and resonances in the dusty disks around other stars, as well as signs that source bodies orbit within. The close elliptical orbits of many large extrasolar planets are best understood as the end result of angular momentum transfer between these bodies and massive disks [see "Migrating Planets," by Renu Malhotra; SCIENTIFIC AMERICAN, September 1999]. Planetary rings are not only striking, exquisite structures; they may be the Rosetta stones to deciphering how planets are born. SA

MORE TO EXPLORE

Observations of Saturn's Ring-Plane Crossings in August and November 1995. Philip D. Nicholson et al. in *Science*, Vol. 272, pages 509–515; April 26, 1996.

The Formation of Jupiter's Faint Rings. Joseph A. Burns et al. in *Science*, Vol. 284, pages 1146–1150; May 14, 1999.

Stability of Neptune's Ring Arcs in Question. Christophe Dumas et al. in *Nature*, Vol. 400, pages 733–735; August 19, 1999.

Planetary Rings. Joseph A. Burns in *The New Solar System.* Fourth edition. Edited by J. Kelly Beatty, Carolyn Collins Petersen and Andrew Chaiken. Cambridge University Press, 1999.

OPPOSITE PAGE: DON DIXON (*drawing*); NASA/JPL (*left*); FROM *NATURE*, VOL. 400, NO. 6746, 1999: B. SICARDY ET AL., CANADA-FRANCE-HAWAII TELESCOPE (*center*) AND C. DUMAS ET AL., HUBBLE SPACE TELESCOPE, JPL AND CALIFORNIA INSTITUTE OF TECHNOLOGY (*right*)