Planetary Rings

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CHAPTER 27

1. Introduction

Planetary rings are those strikingly flat and circular appendages embracing all the giant planets in the outer Solar System: Jupiter, Saturn, Uranus, and Neptune. Like their cousins, the spiral galaxies, they are formed of many bodies, independently orbiting in a central gravitational field. Rings also share many characteristics with, and offer invaluable insights into, flattened systems of gas and colliding debris that ultimately form solar systems. Ring systems are accessible laboratories capable of providing clues about processes important in these circumstellar disks, structures otherwise removed from us by nearly insurmountable distances in space and time. Like circumstellar disks, rings have evolved to a state of equilibrium where their random motions perpendicular to the plane are very small compared to their orbital motions. In Saturn's main rings (Fig. 1), for example, orbital speeds are tens of km/sec while various lines of evidence indicate random motions as small as a few millimeters per second. The ratio of vertical to horizontal dimensions of the rings is consequently extreme: one part in a million or less, like a huge sheet of paper spread across a football field.

Rings, in general, find themselves in the **Roche zone** of their mother planet, that region within which the tidal effects of the planet's gravity field prevent ring particles, varying in size from micron-sized powder to objects as big as houses, from coalescing under their own gravity into larger bodies. Rings are arranged around planets in strikingly different ways despite the similar underlying physical processes that govern them. Gravitational tugs from satellites account for some of the structure of densely-packed massive rings [*see* SOLAR SYSTEM DYNAMICS: REGULAR AND CHAOTIC MOTION], while nongravitational effects, including solar radiation pressure and electromagnetic forces, dominate the dynamics of the fainter and more diffuse dusty rings. Spacecraft flybys of all of the giant planets and, more recently, orbiters at Jupiter and Saturn, have revolutionized our understanding of planetary rings. New rings have been discovered and many old puzzles have been resolved. Other problems, however, stubbornly persist and, as always, new questions have been raised. Despite significant advances over the past decade, it is still the case that most ring structure remains unexplained.

2. Sources of Information

2.1 Planetary Spacecraft

While rings have been observed from the surface of the Earth ever since Galileo Galilei discovered two curious blobs near Saturn in 1610, the study of planetary rings did not emerge as the rich field of scientific investigation it is today until the *Voyager* spacecraft made their historic tours

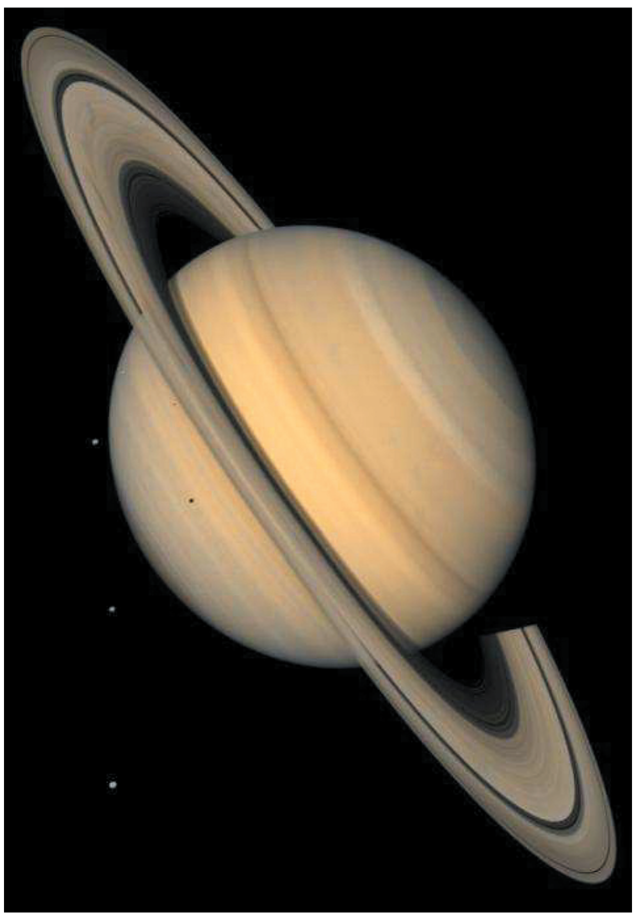

FIGURE 1 Saturn and it main ring system in near natural color as seen from *Voyager*. From bottom, the satellites Rhea, Dione, and Tethys are visible against the darkness of space, with Mimas just above them on Saturn's bright limb. Shadowing abounds in this image: black dots cast by Mimas and Tethys are visible on Saturn's disk, the planet blocks light from getting to the rings at lower right, and the foreground rings paint a dark band on the planet's cloudtops. From the outside are the bright A and B rings separated by the Cassini Division. The narrow Encke Gap in the outer A ring is also visible, as is the dark C ring near set the planet.

of the outer Solar System in the 1980s. Not even the two *Pioneer* spacecraft, the first human artifacts to pass through the realms of Jupiter and Saturn in the mid to late 1970s, hinted at the enormous array of phenomena to be found within these systems.

Voyager 1 arrived first at Jupiter in March 1979, followed by *Voyager 2* four months later. After its encounter with Saturn in November 1980, *Voyager 1* was placed on a trajectory that took it out of the Solar System; *Voyager 2* encountered Saturn in August 1981 and then sailed on to reach Uranus in January 1986, and Neptune, its last planetary target, in August 1989. Each spacecraft was equipped with a suite of instruments collectively capable of covering a wide range of wavelength and resolution. Tens of thousands of images of planetary ring systems in the outer Solar System were acquired by the *Voyager* cameras at geometries and resolutions impossible to obtain from the ground. Also, occultations of bright stars by the rings were observed from the spacecraft, and occultations by the rings of the spacecraft telemetry radio signals were observed from the Earth; both produced maps of the radial architecture of the rings at spatial scales of ~100 m. In addition to these remote-sensing observations, local (or *in situ*) measurements were made of charged particles, plasma waves, and, indirectly, impacts of micron-sized meteoroids as each spacecraft flew through the ring regions of each planet. These data sets contributed in varying degrees to the picture that ultimately emerged of the unique character and environment of the ring systems surrounding the giant planets.

The *Galileo* spacecraft, launched in 1989, became the first artificial satellite of Jupiter in December 1995 and remained in orbit until September 2003 when, fuel running out and instruments ailing, it was directed to crash into the giant planet. Images of the Jovian ring system are few but have improved resolution and image quality significantly over those obtained by *Voyager*. Galileo resolved one of three separate ring components imaged by *Voyager*—the Gossamer Ring—into two distinct structures and clarified the intimate relationship between these components and the nearby orbiting satellites (Table 1, Fig. 2).

The Cassini spacecraft, orbiting Saturn since July 1, 2004, is the best ring-imaging machine built by humans to date. Cassini carries a host of remote imaging and *in situ* instruments that are currently making detailed observation of Saturn, its moons, rings, and magnetosphere. One author of this chapter (CCP) is also the leader of the visual imaging instrument that returned many of the figures displayed in this chapter. Other imaging instruments cover infrared and ultraviolet wavelengths, the radio science package will perform new occultation experiments, and numerous *in situ* experiments are studying local properties of dust, plasma, and magnetic fields.

2.2 Earth-Based Observations

In the past two decades, Earth-based telescopic facilities and instrumentation have become increasingly sophisticated and sensitive; key advances include 10-m class telescopes, active adaptive optics that instantaneously correct for variations in the Earth's atmosphere, and ever-larger arrays of digital CCDs sensitive to visual and infrared light. The Hubble Space Telescope (HST), placed in orbit around the Earth in 1990, nicely complements ground-based instruments by providing unparalleled sharp views and ultraviolet capabilities. Clever observers have taken advantage of these advances, as well as unique geometric opportunities to push beyond spacecraft discoveries, despite the severe distance handicap. These advances have proven invaluable for furthering the study of planetary rings.

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TABLE 1 **Locations of Major Ring Components. The inner limits of Jupiter's Amalthea and Thebe rings are poorly constrained. The Saturnian F ring has multiple narrow strands that are part of a continuous spiral ring in addition to the bright core listed above. The uranian η ring has a diffuse component that extends ∼55 km beyond the ring. R1 and R2 were discovered by HST in 2003. New Saturnian rings discovered by Cassini that lie exterior to the main rings are given below; those within the main rings have been omitted.**

Planet	Ring Component	Radial Location or (width) in km	Optical Depth
Jupiter	Halo	89,400–123,000	10^{-6}
(Radius: 71,492 km)	Main	123,000–128,940	10^{-6}
	Amalthea Ring	140,000?–81,000	10^{-7}
	Thebe Ring	140,000?–221,900	10^{-7}
	Thebe Extension	221,900–280,000	10^{-8}
Saturn	D	67,000–74,500	10^{-5}
(Radius: 60,330 km)	C	74,500–92,000	0.05–0.35
	B	92,000–17,580	0.4–>3
	Cassini division	117,580–122,200	0–0.1
	A	122,200–136,780	0.4–1.0
	R/2004 S1 (Atlas)	137,630	$\sim 10^{-4}$
	R/2004 S2	138,900	$\sim 10^{-5}$
	F	140,200 (∼1)	0.1–1
	R/2006 S1 (Janus/Epimetheus)	151,500	?
	G	166,000–173,000	10^{-6}
	R/2006 S2 (Pallene)	212,000	?
	E	181,000–483,000	10^{-6}
Uranus	1986 U2R	∼38,000	?
(Radius: 26,200 km)	6	41,837 (1.5)	0.3
	5	42,234 (∼2)	0.5
	4	42,571 (∼2)	0.3
	α	44,718 (4–10)	0.4
	β	45,661 (5–11)	0.2
	η	47,176 (1.6)	<0.4
	γ	47,627 (1–4)	>0.3
	δ	48,300 (3–7)	0.5
	λ	50,024 (∼2)	0.1
	ε	51,149 (20–96)	0.5–2.3
	R2	66,100–69,900	10^{-8}
	R1	86,000–103,000	10^{-8}
Neptune	Galle	41,000–43,000	10^{-4}
(Radius: 25,225 km)	Le Verrier	53,200 (<100)	0.01
	Lassell	53,200–59,100	10^{-4}
	Arago	57,200 (∼10)	?
	Adams	62,933 (15–100)	0.01–0.1

2.2.1 STELLAR OCCULTATIONS

A stellar occultation occurs when, as viewed from Earth, a bright star passes behind a planetary ring system. These events occur rarely, typically last for hours, and can yield data on the location of ring features that rival spacecraft resolutions. The Uranian ring system was discovered in 1977 by stellar occultation, and the first hint of the Neptunian ring arcs also came during such an event. The value of these observations is dramatically illustrated by the 1989 occultation of a particularly bright star by Saturn's ring system that revealed numerous ring features to a precision of 2 km, produced an important refinement of Saturn's pole

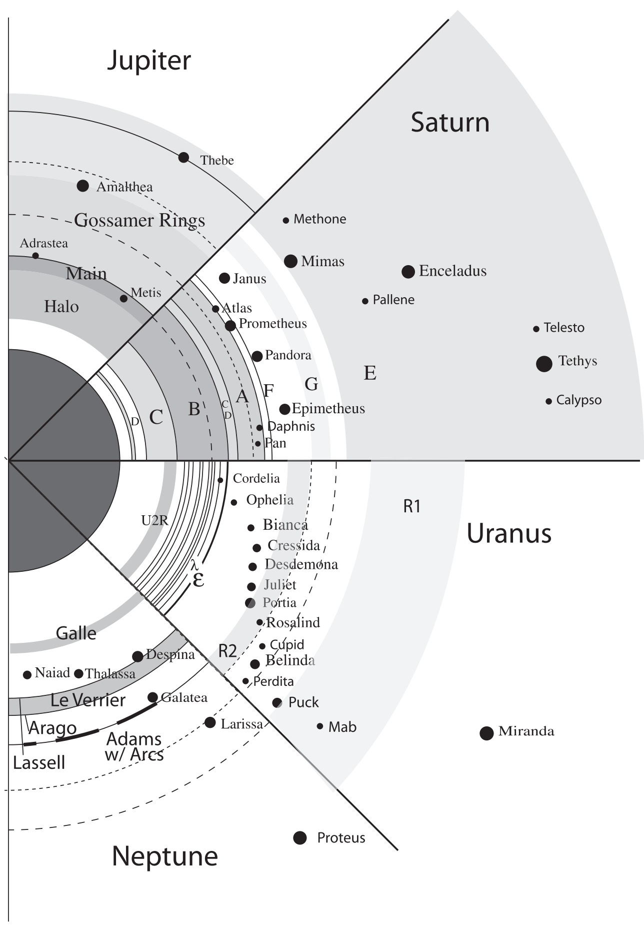

FIGURE 2 A graphic schematic of the ring-moon systems of the giant planets scaled to a common planetary radius (compare with Table 1). The planet is the solid central circle, ring regions are shaded, and nearby satellites are plotted at the correct relative distances. Dotted lines indicate the Roche radius for a satellite density of 0.9 g/cm^3, and dashed lines show the position of synchronous orbit where an object's orbital period matches the planetary rotation period. The Roche radius is outside the synchronous distance for Jupiter and Saturn but inside it for Uranus and Neptune due to the more rapid spins of the larger planets. (Figures courtesy of Judith K. Burns)

position, and allowed the two million-year precession period of the pole to be measured for the first time. The prevalence of collisions amongst particles in Saturn's main rings causes the rings to be extremely thin and exactly perpendicular to Saturn's pole, enabling this interesting observation; this is perhaps the longest-period astronomical motion measured to date.

2.2.2 RING PLANE CROSSINGS

Ring plane crossings (RPXs), those times when the plane containing a planet's rings sweeps over the Earth or the Sun as the planet moves along its orbital path, are unique observational opportunities. Near these special times, the Sun and the Earth can be on opposite sides of the ring plane, above or below it by just a few degrees or tenths of a degree. The near edge-on aspect of planetary rings in this geometry and our view of the unilluminated side drastically reduces the glare of sunlight scattered off or through the rings and allows nearby faint objects to be much more easily seen. Five small satellites of Saturn were discovered during past RPXs: Janus (in 1966) and Epimetheus, Telesto, Calypso, and Helene (in 1980). [*See* OUTER PLANET ICY SATELLITES] Saturn's outer dusty E ring (Fig. 2) was also discovered during the 1966 RPX and its strange bluish color revealed in the 1980 RPX. The most recent crossing, which occurred from 1995–1996, showed the F-ring (Fig. 2) to be slightly tilted, revealed a number of clumps in the F-ring that appear and disappear, constrained the thickness of the main rings to be less than 1.5 km (the apparent thickness of the outer F-ring), recovered several tiny satellites not seen since the *Voyager* flybys, and further refined Saturn's pole position and its precession rate. In addition, light filtered through the optically thin regions of the rings has allowed these diffuse structures to be studied in a unique way.

Ring plane crossings occur twice per orbit, roughly every 6, 15, 43, 82 years for Jupiter, Saturn, Uranus, and Neptune, respectively. Upcoming RPXs for these planets occur in 2009, 2009, 2007, and 2046, making the next few years an exciting time for ring scientists. One author of this chapter (DPH) has been involved in RPX observations of Jupiter, Saturn, Uranus, and even Mars (which is predicted to have an extremely faint ring derived from material lofted from its two small moons).

2.3 Numerical Studies

Continuous advances in the speed and design of desktop computers have made numerical studies of ring systems an essential tool for investigating dynamically important factors that are not easily treated by analytical methods. Numerical methods have been used to simulate a myriad of ring processes, including the collisional and gravitational interactions among orbiting ring particles, the effects of micrometeoroid impacts onto the rings, the behavior of small charged ring particles under the influence of rotating magnetic fields, and the evolution of debris resulting from a catastrophic disruption of a satellite orbiting close to or within a planet's Roche zone. Key algorithm advances over the past decades include energy-preserving "symplectic" codes, which can efficiently integrate the exact forces arising in a collection of interacting bodies, and significantly faster "tree" codes, optimized for large collections of interacting bodies, which employ clever approximations to the exact equations of motion. Numerical models are an important tool for scientists seeking to understand the physical processes active in known ring features. These simulations, when targeted well, can also make testable predictions, in some cases steering observers toward refining their observational strategies.

3. Overview of Ring Structure

Rings are characterized by an enormous variety of structural detail, only some of which has been attributed successfully to known physical processes, either internal or external to the rings (Section 4). Looking across all four ring systems, however, we do find trends and commonalities. In particular, we now recognize three main types of planetary rings in the Solar System. First are broad massive rings, replete with fine-scale structure. Some of this structure is produced by embedded moonlets and some by interactions with both nearby and distant satellites. Saturn's extensive main ring system provides the only example of this type (Fig. 1). The second ring type consists of sets of sharply defined narrow rings, interspersed with small moons. These narrow structures are found primarily at Uranus and Neptune, although Saturn has interesting examples: its F-ring and numerous ringlets in the fainter C and D rings (Fig. 2). Finally, all of the giant planets have broad relatively featureless sheets of dusty debris that are usually found in close association with small source satellites. Jupiter's ring system provides the best understood archetype, but numerous additional examples are found around each of the other giant planets.

3.1 Jupiter

The particles comprising the diffuse tenuous rings of Jupiter almost certainly have their origin in the release of dust from each of the four moonlets—Adrastea, Metis, Amalthea, and Thebe—embedded in the rings. These small rocky objects are continually pummeled by bits of space debris that are accelerated to high relative speeds by Jupiter's intense gravity. When struck by this flotsam, puffs of dust are ejected from the moonlet surfaces. The main ring of Jupiter has a small normal optical depth, $\tau_N \sim 10^{-6}$, in tiny (<10 μm) particles; the optical depth may be even smaller for large (>1 mm) particles (Fig. 3). The main ring has a relatively sharp outer edge suspiciously coincident with the orbit of Adrastea; just interior to this, the satellite Metis creates a depression in ring brightness. The fact that the main ring extends only inward from the small source satellites strongly suggests that ring particles drift inward. A ~20,000-km vertically thick toroidal ring, or halo, lies interior to the main ring (Fig. 4). Its normal optical depth is comparable to the main ring, a fact that is consistent with inward drift. It took the arrival of the *Galileo* spacecraft to show that the diffuse material exterior to the main ring was, in fact, split into two components, each associated with a small moon (Fig. 5). As with the main ring, these gossamer rings extend primarily inward from their source moons Thebe and Amalthea and, moreover, have vertical thicknesses that exactly correspond to the vertical motions of the inclined moons (Fig. 6). An extremely faint outer extension to the Thebe ring is composed of particles on significantly eccentric orbits. *Cassini*'s

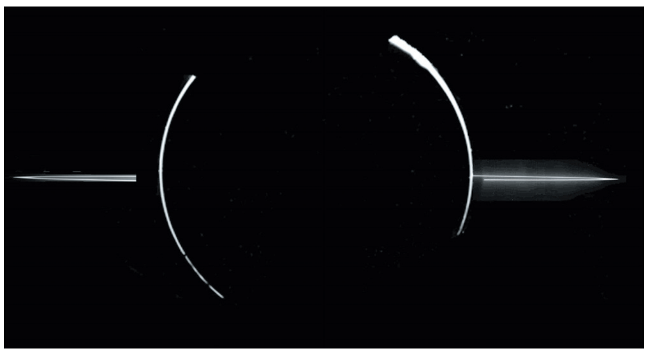

FIGURE 3 A *Voyager* mosaic of images taken from Jupiter's shadow looking back toward the Sun. Sunlight traces out the edge of the planet's atmosphere and the distribution of micron-sized dust in its main ring. The gap between one ring arm and the planet on the right is due to Jupiter's shadow; the gap in both arms on the left is an artifact from the stitching together of multiple images.

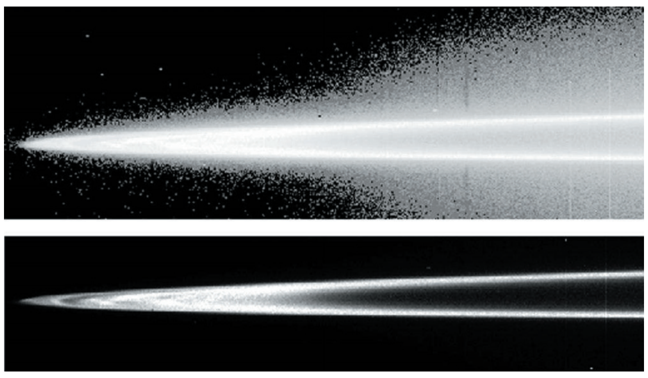

FIGURE 4 A *Galileo* image showing Jupiter's main ring (lower panel) and main ring plus interior halo (top panel). Note the patchiness of the main ring, hinting at further complexity.

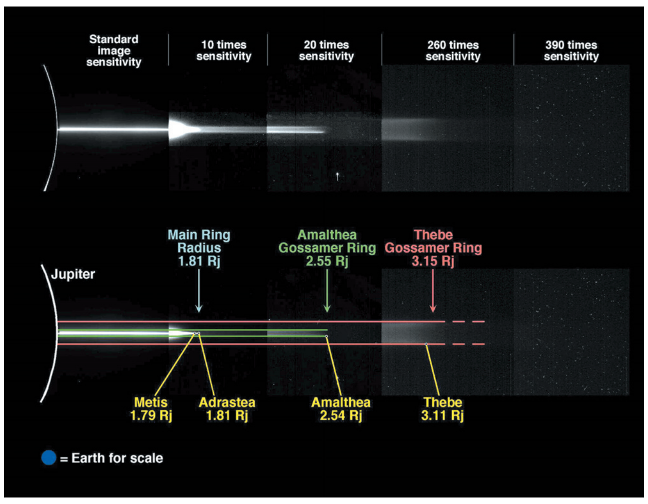

FIGURE 5 A mosaic of *Galileo* images enhanced to bring out faint jovian ring features. The main ring shows up clearly in standard images, while the jovian halo and Amalthea ring become apparent only in enhanced images. The outermost Thebe ring appears only in images with the greatest sensitivity.

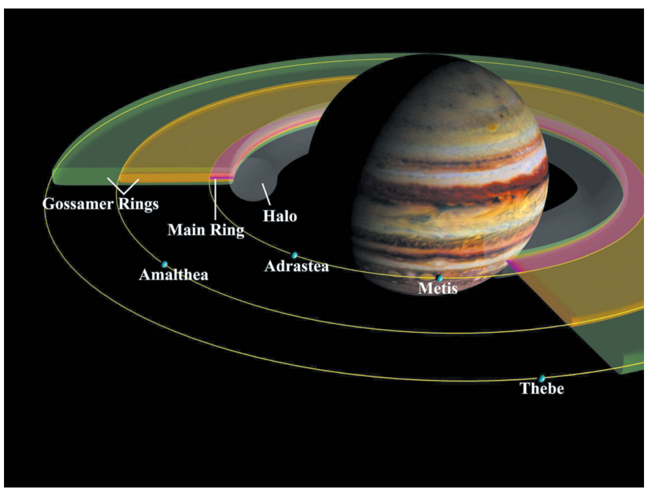

FIGURE 6 A schematic of Jupiter, its innermost four moonlets, and its ring components (shown in different colors) as determined by *Voyager*, *Galileo*, and ground-based observations. Note that the thickness of the inner Halo component is due to an electromagnetic effect operating on dusty grains, while the vertical extension of the Gossamer rings have a more prosaic cause: the tilted orbits of the source satellites themselves.

flyby of Jupiter revealed that, similarly, the vertical motions of metris, and possibly Adrastea. The jovian ring particles have reddish colors, suggestive of a silicate or carbonaceous composition, just like the embedded moonlets.

3.2 Uranus and Neptune

Ground and space-based observations reveal ten, narrow, sharp-edged continuous rings encircling Uranus (Fig. 7). Interspersed amongst these features are broad dusty swaths of material best seen when Voyager was looking back at Uranus from a vantage point further from the Sun (Fig. 8). In addition, HST has recently detected two distant and extremely faint dust sheets similar to those around Jupiter (R1 and R2 in Fig. 2). Most of the narrow rings are eccentric and some are tilted relative to Uranus' equator plane by a few hundredths of a degree. Since a ring of colliding debris left to itself would spread in radius, rings with sharp edges require some confining mechanism. In the case of the outermost ring, ε, gravitational perturbations from two small neighboring satellites on opposite sides of the ring play a key role (Fig. 7). If the mass of the satellites dominate that of the ring, then radial spreading is significantly slowed because the spreading is now applied to the total mass of the system: ring plus satellites. The situation is analogous to a pair of runners standing back to back. The runners can separate rapidly if unopposed, but if each is forced to push an automobile ahead of him or her, they separate much more slowly. It is suspected that the other Uranian rings may also have so-called shepherding satellites, but because these objects have not been spotted yet, they must be smaller than *Voyager* and now Hubble Space Telescope limits of ~ 10 km.

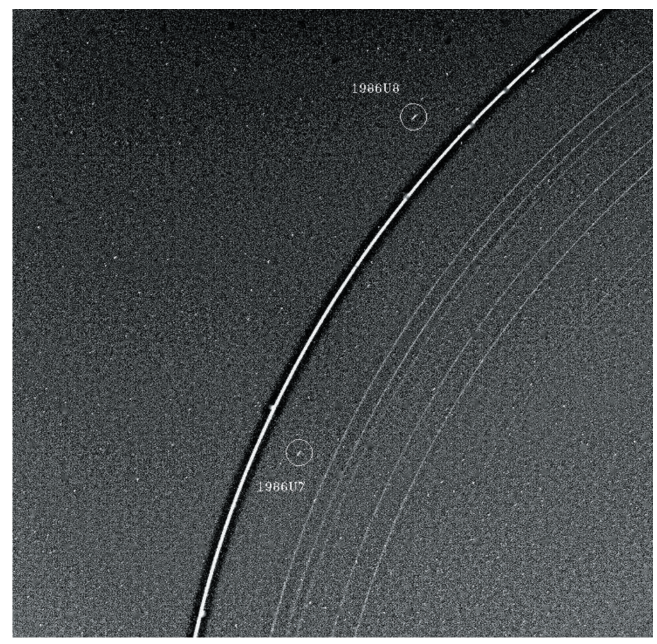

FIGURE 7 The outermost ε ring of Uranus, shepherded by the small satellites Cordelia (1986U7) and Ophelia (1986U8). The ε ring is noticeably brighter and wider than the other uranian rings. Heading inward, the first triplet of rings are δ, γ, and η; the next pair are β and α, and the final triplet (barely visible) are the 4, 5, and 6 rings. The satellites are smeared azimuthally by their orbital motion during the exposure. [*See* PLANET SATELLITES]

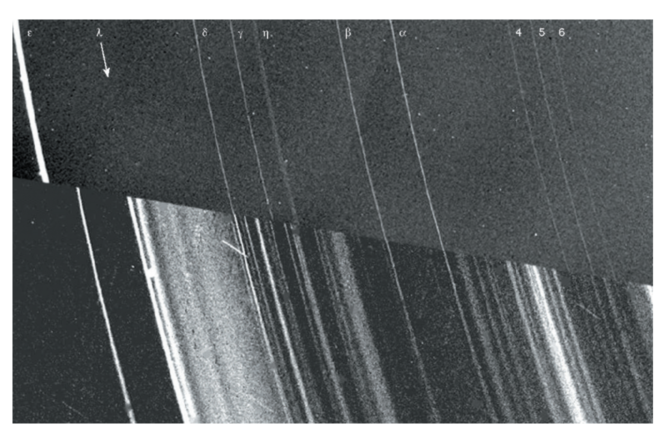

FIGURE 8 A comparison of *Voyager 2* images of the uranian rings taken looking away from the Sun (upper panel) and toward the Sun (lower panel). The latter geometry highlights rings composed of small dust grains. Short line segments in the lower panel are star trails; these attest to the long exposure time needed to highlight the faint dusty features. Note that not all rings features line up perfectly, implying eccentric orbits, particularly in the case of the ε ring (far left). Note that the narrow λ ring and many broad dusty features are visible only in the lower panel. The bright feature visible at the extreme right of the lower plot is the 1986 U2R ring.

HST observations of Uranus in 2003 discovered two new moons of this size; when the instrument is trained on Uranus during the upcoming Uranian ring plane crossing, moonlets as small as six km should be revealed. It will be interesting to see if these observations find that some of the missing shepherds are, in fact, loyally tending their flocks.

Returning to the ε ring, it is thought that some combination of internal self-gravity and interparticle collisions is probably responsible for maintaining the ring's eccentric shape (Fig. 8) and tilted aspect. These effects must be strong enough to enforce uniform precession, since the ring is observed to change its orientation in space as if it were a rigid body. Several other of the less massive and less optically thick uranian rings (e.g., δ and γ) are also tilted and eccentric, and the λ ring has an unexplained five-lobed azimuthal pattern. These mysteries are all waiting to be solved.

Two broad diffuse rings and two narrow denser ones encircle Neptune (Fig. 9). The outermost one, the Adams ring, contains the set of discrete, clustered, narrower- and denser-than-average arc segments for which Neptune has become famous (Fig. 10). The Adams ring is at least partially confined, both radially and azimuthally, by a single satellite Galatea. Other small satellites orbit in and amongst the Neptunian rings (Fig. 2) in a configuration that is somewhat reminiscent of the Jovian system.

Extensive sheets of icy powder, like fine snow, particularly conspicuous when backlit by the Sun, fill in the ring systems of Uranus (Fig. 8) and, possibly, Neptune (Fig. 9). These structures, though poorly understood, are probably similar to the more-extensively observed dusty rings of Jupiter and Saturn. There are significant differences though, as the optical depths vary by nearly a factor of a million from the extremely tenuous uranian R1 and R2 rings, through the not-so-faint jovian and saturnian dust sheets, to the more robust structures, like Galle and Lassell, located near Uranus and Neptune (Table 1). Hopefully these enigmatic structures will become better understood over the next several years.

3.3 Saturn

Finally, the rings of Saturn (Figs. 1 and 11), containing as much mass as the 200-km radius Saturnian satellite, Mimas, are home to almost all the ring phenomena described earlier and more: empty gaps in the rings whose widths vary with longitude (Fig. 12), narrow uranian-like rings (Fig. 13), ghostly time-variable radial markings called spokes (Figs. 14 and 15), spiral corrugations and density enhancements that tightly wind around the planet while slowly diminishing in amplitude (Fig. 16), and more. The ring system has now fallen under the sharp scrating of the *Cassini* spacecraft, and significant advances in the survey of its ring phemonology have been made as a result. Saturn's rings are the only ones whose composition is known with certainty: they are made predominantly of water ice, whereas rocky material seems most likely at Jupiter, and mixtures of ammonia and methane ices coated with carbon are plausible constituents of the much darker rings of Uranus and Neptune. The main saturnian rings consist of the classical components seen from Earth: A, B, and C (Figs. 1 and 11). The narrow F ring (Fig. 13) immediately outside the main rings was discovered by *Pioneer* and has been the subject of intense investigation and speculation; the innermost D ring and the tenuous G ring were not clearly identified as rings until *Voyager* arrived in the system in 1980. Hidden from ground-based telescopes by its intrinsically low optical depth and the bright glare from nearby Saturn, the D ring has recently been revealed by *Cassini* to be extremely complex and dynamic (Fig. 17). Structures seen by *Voyager* 1980 are absent

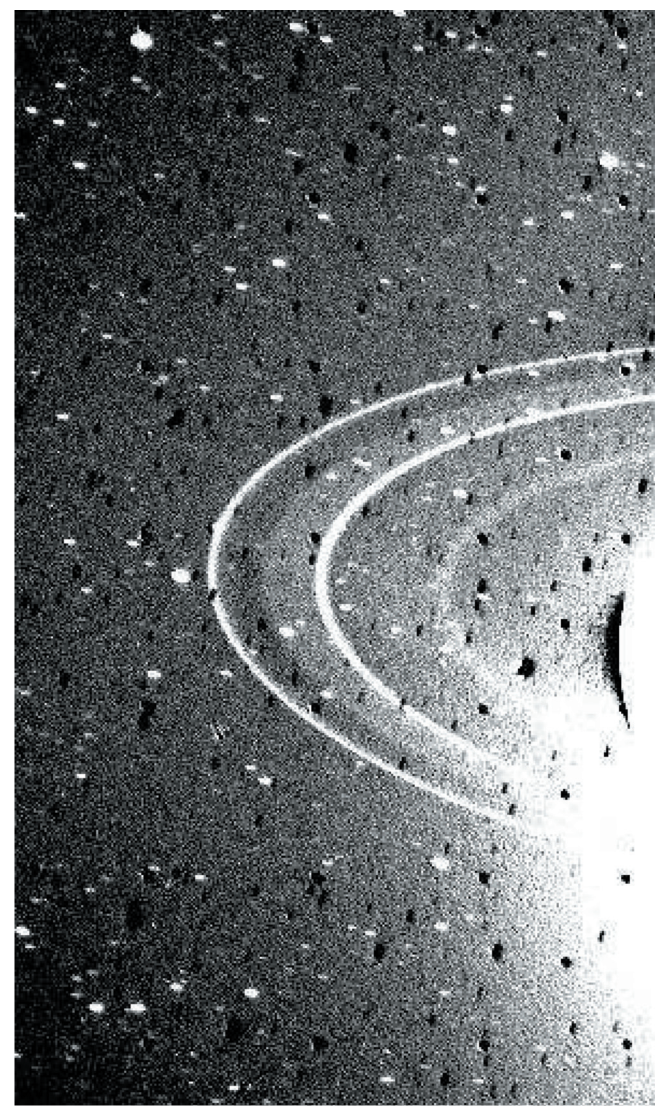

FIGURE 9 A long exposure of Neptune (on the right) and its ring system. The salt and pepper splotches are due to cosmic ray hits. Midway between the bright Le Verrier and the outermost Adams rings is the much fainter Arago ringlet and the broad Lassell ring extending inward to Le Verrier. The innermost ring, Galle, is also visible.

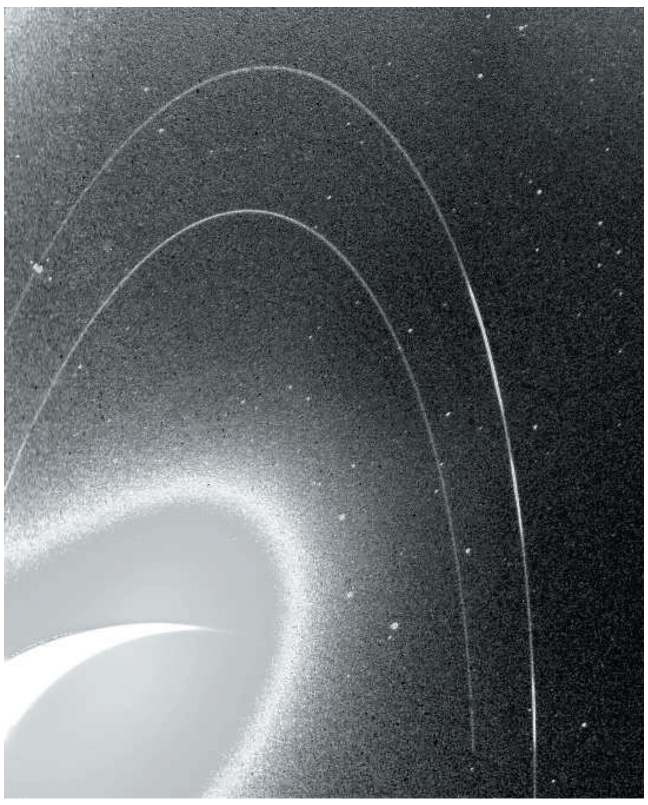

FIGURE 10 The brightest two neptunian rings, Le Verrier (inner curve) and Adams (outer curve) are revealed in this *Voyager* image. Neptune is overexposed to lower left, indicating the difficulties faced in searching for faint features near planets. A short-exposure crescent-shaped Neptune has been overlayed to indicate the planet's true size and phase. Three of the famous ring arcs are visible in the outer Adams ring, while the Le Verrier ring has no such features.

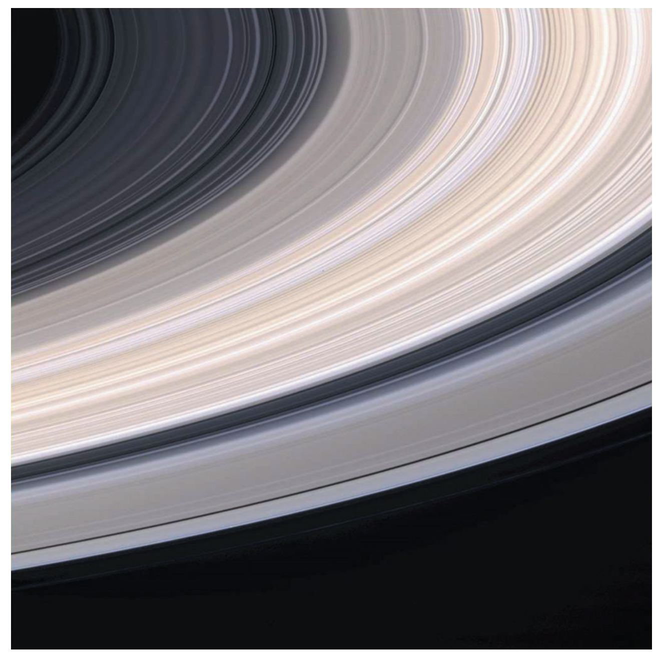

FIGURE 11 A beautiful natural-color view of Saturn's rings from *Cassini*. From upper left are the dark C ring, with intricate substructure, the bright sandy-colored B ring, the dark Cassini division, and the grayish A ring. The narrow Encke gap and the narrow faint F ring are clearly visible, about equidistant from the A ring's outer edge. Saturn's rings are made primarily of water ice. Since pure water ice is white, the different colors in the rings probably reflect varying amounts of contamination by exogenic materials such as rock or carbon compounds.

in *Cassini* images today and vice versa. Strange periodicities near the C-ring boundary may hint at the cause of the dramatic drop in optical depth that occurs there. The very broad outer E ring, whose particle number density peaks at the orbit of Enceladus, appears to be produced from particles liberated from the satellite's interior by volcanic processes (Fig. 18). Its nature, and that of the G ring, has been delineated with increasing accuracy by Earth-based observations made during the ring-plane crossing events in 1995. *Cassini's* onboard dust detector finds that the E ring extends out nearly to the orbit of Titan, over 500,000 km beyond the outer visible boundary listed in Table 1.

4. Ring Processes

The fact that certain architectural details are common to all ring systems speaks of common physical processes operating within them. To date, only a subset of planetary ring features can be confidently explained. Here we break down the physical processes believed to be responsible for the creation of ring features into two categories: internal and external. Internal processes are present, to some extent, in all rings, while external processes arise when we consider the particular environments in which rings systems are located.

4.1 Dense Rings: Internal Processes

Dense rings with closely packed constituent particles are shaped strongly by collisions and self-gravity; in the denser parts of Saturn's rings, individual particles experience collisions hourly, upwards of 10 times per circuit of Saturn. Faint dusty rings, by contrast, are relatively unaffected by these processes; for example in Jupiter's outer gossamer rings, a dust grain might orbit the planet 10 million times (for 10,000 years) before experiencing a collision and the effects of self-gravity are similarly reduced. This subsection covers the physics that plays a role in the densest rings of Saturn, Uranus, and Neptune.

Two physical concepts underlie the internal workings of dense ring systems: the presence of a forced systematic change in orbital speeds across the rings (the so-called Kepler shear), and the dissipation of orbital energy that arises from the presence and the inelastic nature of

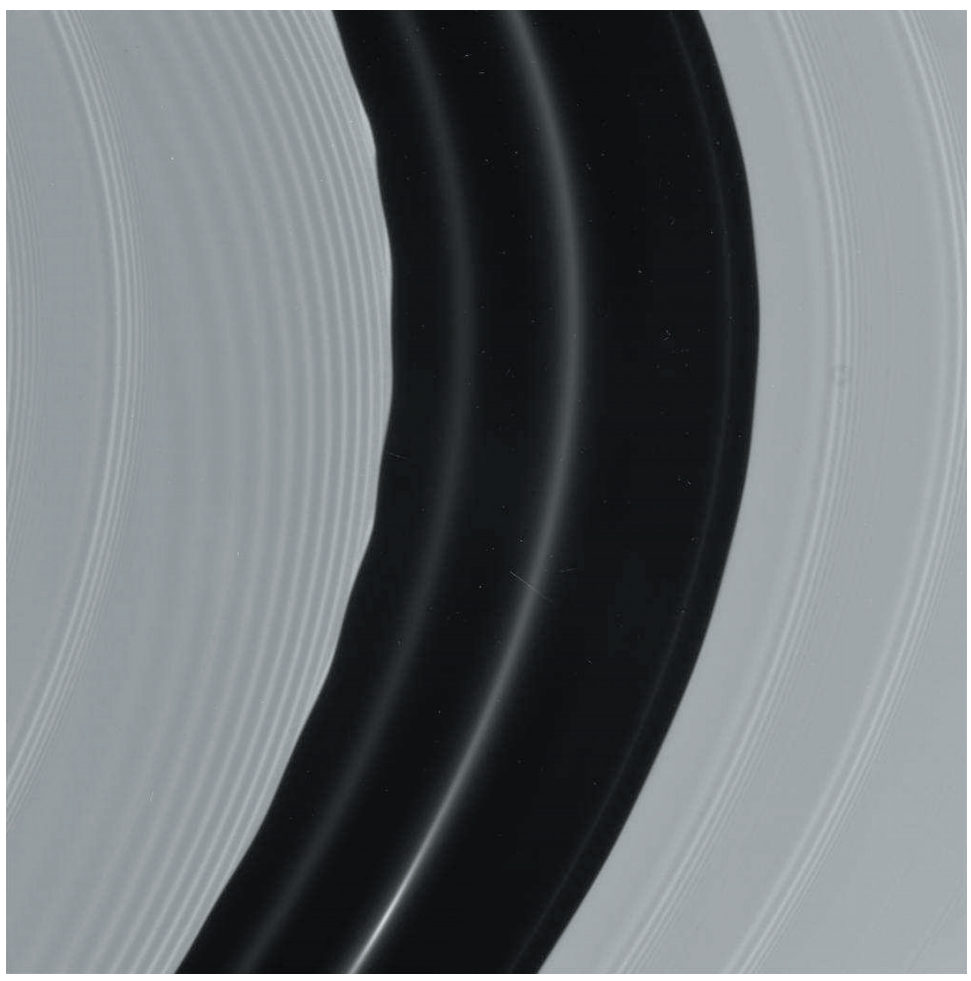

FIGURE 12 This *Cassini* image is a close up of the lit face of Saturn's A ring showing exquisite details in the Encke gap. Several faint narrow ringlets are visible; the brightest central one is coincident with the orbit of the tiny moon Pan. The wavy inner edge of the gap and the spiral structures wrapping inward are also caused by Pan. The waves on the inner gap edge lead Pan, while similar waves on the outer gap edge (not seen) trail it.

collisions among ring particles. Collisions between particles, which occur regularly due to differential orbital speeds, force random motions amongst the particles. These random motions can also be diminished in collisions, as energy is lost to the chipping, cracking, compaction, and sound propagation through the particles. A balance is struck, with the details determined by the number of collisions forced by Kepler shear and the inexorable loss of energy during these and subsequent inelastic collisions. Collisional processes can also alter ring particle sizes and shapes, resulting in the erosion and smoothing of surfaces in some cases and the accretion or sticking of particles in others.

Significant progress has been made in the theory of dense rings by treating the rings as fluids; this prescription is called kinetic theory. Kinetic theory shows that collisional equilibrium is achieved after several orbital periods and yields a monotonically decreasing relation between the particle random velocities, $\sim v$, and the overall optical depth, τ. That is, in steady state each ring region is characterized by a particular optical depth (or surface mass density Σ) and has a typical value for the random velocities of its constituent particles. At low τ, the random velocities and ring thickness tend to be larger, while at high τ the reverse is true. The details of the equilibrium depend on the kinematic viscosity, ν of the ring particles, a quantity that measures the tendency for a fluid to resist shear flow. Like the coefficients of friction for sliding and rolling bodies (e.g., sleds and cars), ν must usually be empirically determined.

In a disk system of colliding particles following Kepler orbits, the faster particles are on the inside, and so collisions naturally transfer angular momentum outward across the disk. Kinetic theory shows that the rate of flow is related to the product $\Sigma\nu$, which is crudely the number of collisions times the effect of a single collision. Thus narrow rings must spread in time, unless another process prevents them from doing so. This conclusion can also be reached by realizing that a narrow ring has more orbital energy than a broad ring with the same mass and angular momentum. Since collisions always deplete orbital energy and do not affect the total angular momentum, all rings are inexorably driven to spread toward the lower energy state.

FIGURE 13 This *Cassini* image reveals details of Saturn's mysterious F ring that lies just outside the A ring (lower right). The bright core of the F ring stands out crisply, embedded in parallel bands of fainter material. A wispy, ribbon-like feature points accusingly at the inner shepherding moonlet, Prometheus, whose eccentric orbit brings it near enough to the ring to strip some material away.

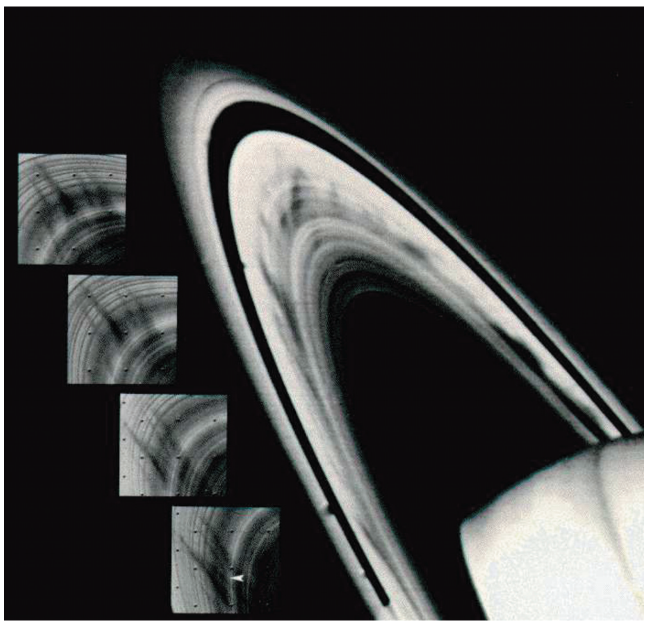

FIGURE 14 A *Voyager* image of dark spokes seen against Saturn's sunlit B ring. Small dust particles appear dark under this lighting condition, hinting at the still poorly understood physical processes behind spoke creation. The inset panels show the change of a given feature with time.

Distinctly different ring regions can exist in near-equilibrium (but the entire ring will still spread) if they have similar values of $\Sigma\nu$. Basic kinetic theory, for example, predicts that two ring regions with different values of the optical depth might have the same $\Sigma\nu$, allowing distinctly different contiguous ring regions to potentially coexist in equilibrium. This mechanism was regarded as a possibility for explaining the large degree and variety of ring structure in Saturn's B ring (Fig. 11) until laboratory measurements on ice particles indicated that the particles were stickier than expected. This implied that the rings were less extended vertically and the particle number densities larger than originally believed, so much so that the precepts of simple kinetic theory were violated.

When it was recognized that very dense rings with highly inelastic collisions violate the principles of kinetic theory on which much of ring theory was based, it became necessary to introduce a new effect into the theory: the transport of angular momentum (via sound waves) across a tightly packed system of orbiting particles. The result of adding this effect, which becomes important in high τ regions, was to change the dependence of $\Sigma\nu$ on τ to a monotonically increasing function. On the basis of this conclusion, it seemed impossible for ring regions of differing optical depth, and therefore

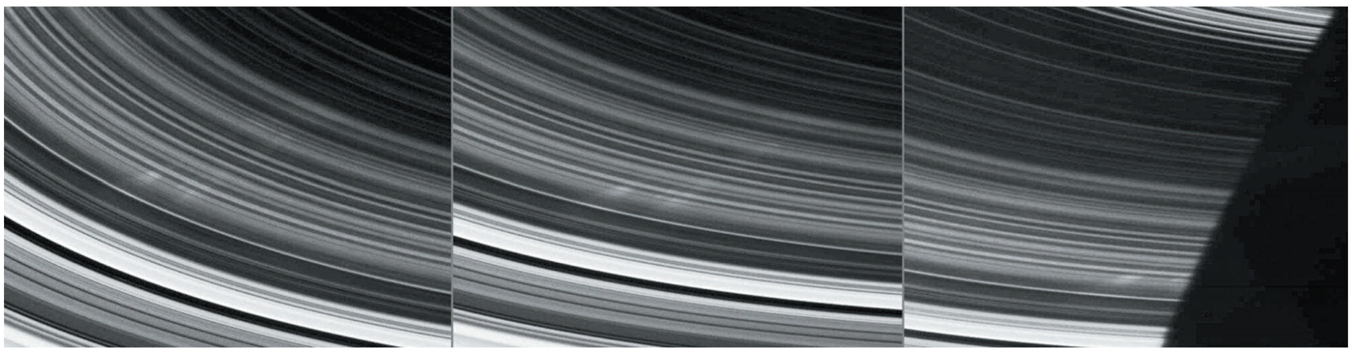

FIGURE 15 A three-panel *Cassini* image of bright spokes seen against the dark side of Saturn's B ring. Small dust particles appear bright under this lighting condition. The motion of the spokes can be seen clearly by comparing the three panels.

differing natural angular momentum flow (proportional to $\Sigma\nu$), to exist stably side by side.

Other possibilities, however, have been suggested to explain the fine-scale structure within a dense ring like the saturnian B ring. These suggestions include adjacent narrow ring regions alternating in behavior between a liquid and a solid and the possibility that density waves may be driven to the point of instability in very dense ring regions. A sea of embedded bodies too small to open gaps and too faint to be noticed by spacecraft could control much of the structure; Pan (responsible for the Encke Gap) and Daphnis (the newly-discovered Keeler-Gap moonlet), may be just the tip of this particular iceberg (Fig. 19). Additional evidence for tiny embedded moonlets comes from particles

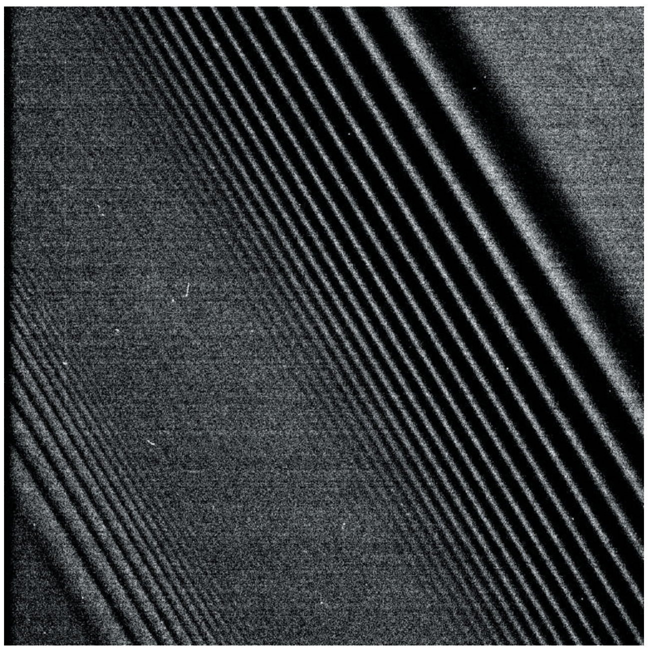

FIGURE 16 This is a narrow-angle *Cassini* image of the dark side of Saturn's A ring. Amazing detail of the Prometheus 12:11 density wave in the lower left part of the image and the Mimas 5:3 bending wave to the upper right are apparent. These features wind around Saturn literally dozens of times before fading into invisibility.

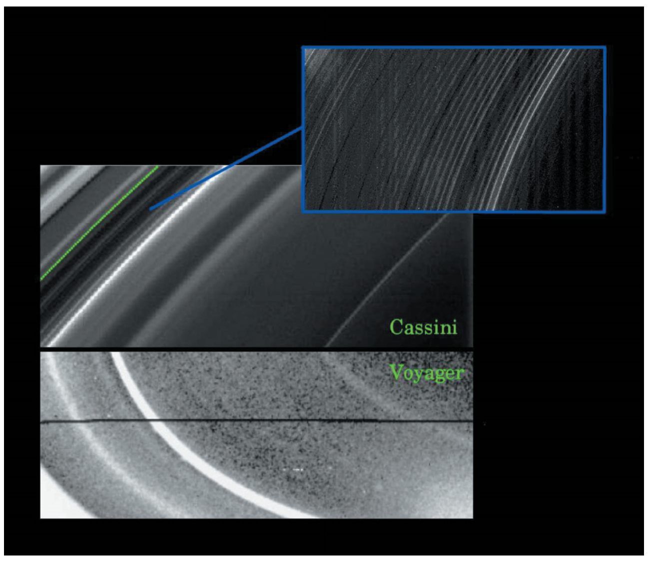

FIGURE 17 A comparison of *Voyager* and *Cassini* images of Saturn's inner D ring (see Table 1). Some differences in the two images are apparent; the brightest *Voyager* ring appears to have shifted inward in the new *Cassini* data. The regular pattern shown in the inset appears just inward of the C ring (bright upper and lower left corners). It has been suggested that this feature is due to collision of a meteoroid into a C- or D-ring parent body just 20 years ago.

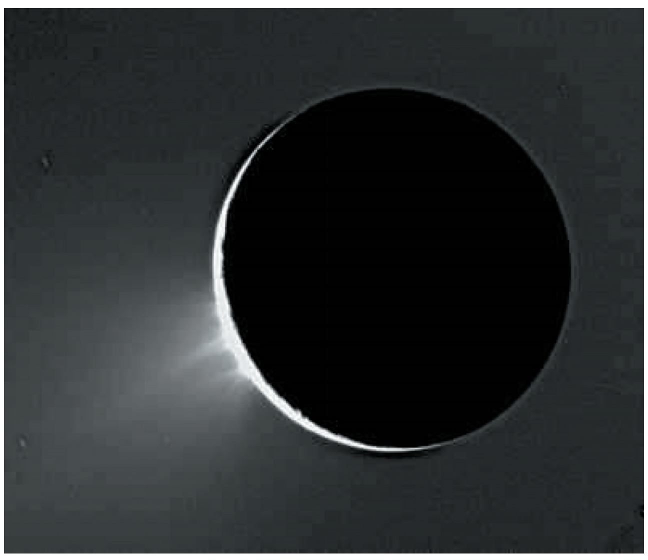

FIGURE 18 This dramatic *Cassini* image of Saturn's icy satellite Enceladus shows tiny particles ejected violently from near the satellite's south pole. These icy grains are destined to join Saturn's diffuse outer E ring.

organized into theoretically-predicted "propeller" shapes, which are beginning to be found in *Cassini* images.

Saturn's outer A ring also exhibits a strange so-called quadrupole asymmetry that manifests itself as alternating 90-degree swaths of brighter and darker regions. This asymmetry has been seen optically and with Earth-based radar, and is best explained by narrow wakes in the ring, oriented obliquely at a given angle. These wakes are thought to be caused by the gravitational clumping of ring particles into temporary agglomerations, as might be expected of material near the edge of the Roche zone (see Fig. 2).

Our understanding of very dense rings is far from complete, and we must regard the bulk of the exquisite structure in Saturn's main ring system as mostly unexplained. New data, mysteries, and ideas have started to emerge from the *Cassini* mission though, so in time new insights and explanations will follow.

4.2 External Causes of Ring Structure

All planetary rings interact with their local environment via long-range forces, and they are also subject to incident

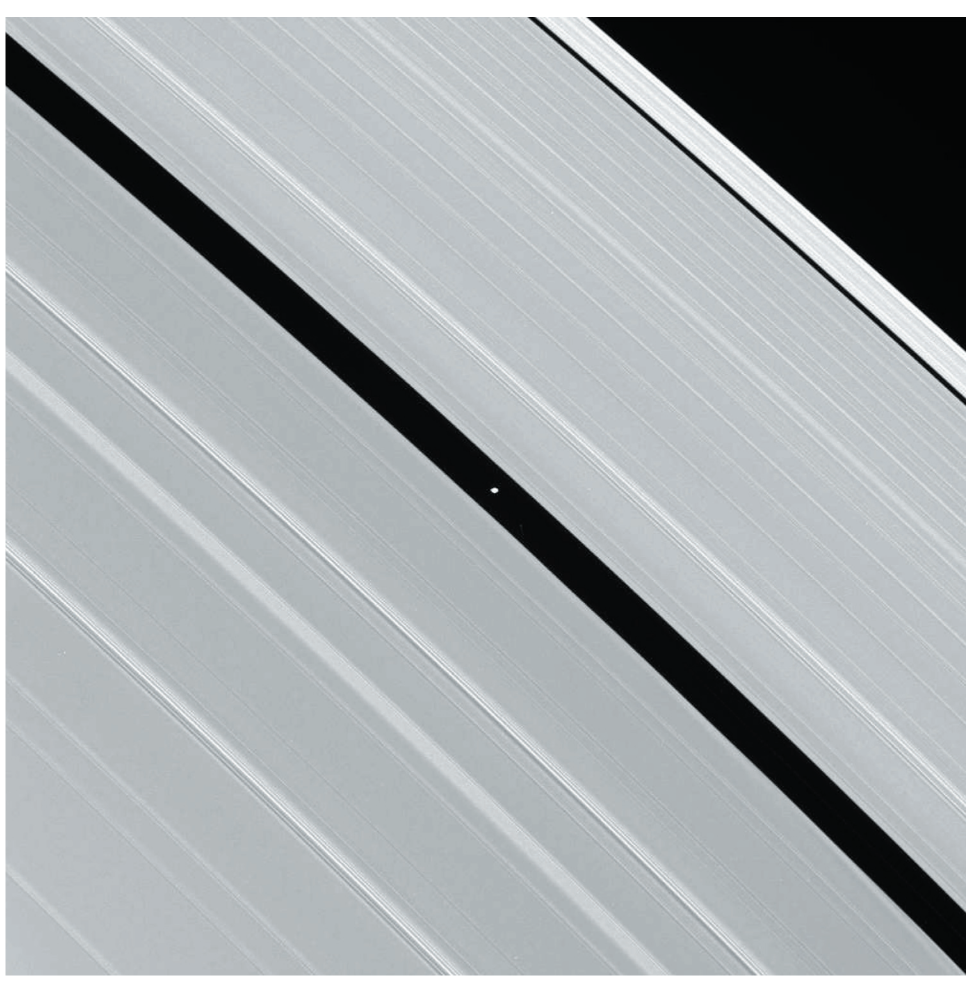

FIGURE 19 A *Cassini* image of the Saturn's outer A ring. The Encke gap slashes a diagonal through the center of the frame and the narrower Keeler gap is also visible at upper right. Both features arise from the action of embedded moons; Pan (centered in the images) opens the Encke gap while Daphnis (not visible) is the cause of the Keeler gap. Many of the bright lines running across the image are resonant features forced by external satellites.

mass fluxes from interplanetary debris. External gravitational forces from other satellites and the nonspherical shape of the planet itself can imprint wavelike signatures in dense planetary rings. Faint dusty rings are also subject to solar radiation pressure, electromagnetic interactions, and different kinds of drag forces. Finally, an external flux of interplanetary debris strikes satellites embedded in rings as well as larger ring particles, cratering their surfaces and ejecting large amounts of additional ring material. This incident debris can also color, chip, erode, and catastrophically fragment ring particles.

4.2.1 EXTERNAL GRAVITATIONAL FORCES

All rings in the Solar System circle planets that are somewhat flattened due to their rapid spin rates. An extra gravitational perturbation arises from this planetary oblateness and slightly adjusts a ring particle's oscillation frequencies in the radial, vertical, and azimuthal directions. The main outcome is orbital precession, which causes tilted and/or elliptical orbits to slowly shift their spatial orientations. More dramatic effects occur for time-variable gravitational forces such as those arising from orbiting satellites and, potentially, a spinning lumpy planet. The perturbations are concentrated at discrete orbital locations known as resonances, where a frequency of external forcing matches a natural orbital frequency of the system. Some forcing frequencies match a natural radial frequency and affect the ring's surface density in a systematic way; others match a natural vertical frequency and lead to warped corrugations in the ring. In both cases, resonances enable the external perturber to exchange energy and angular momentum with particular locations in the ring.

Operating over sufficiently long time scales, satellites can create a staggering variety of features in planetary rings. The degree to which external perturbations on ring particle orbits will create visible disturbances in a broad featureless disk system depends on the ring's natural ability to keep up with the rate of change in angular momentum imposed on it by the external perturbation. If the angular momentum is removed or deposited by external means at a rate that is less than the ring's ability to transport it away from the excitation region (proportional to $\Sigma\nu$), then the ring response will take the form of a wave. If the rate of removal or deposition is greater, however, then the rings will respond by opening a gap, i.e., the particles themselves must physically move, carrying angular momentum with them, to accommodate the external driving force.

The satellite Mimas is responsible for the strongest resonances within Saturn's rings; it causes the Cassini Division, the 4700-km gap between the A and B rings (Fig. 1). Two smaller but closer moons, Janus and Epimetheus, cause the sharp outer edge of the A ring. Detailed inspection of these ring edges by *Voyager* and *Cassini* reveal two- and seven-lobed patterns of radial oscillations, signatures of the specific resonances responsible, but *Cassini* has found significant and complex deviations from these simple patterns. These two dense rings contain many additional examples of features caused by external perturbations of satellites. For example, the 320-km-wide Encke gap in the outer A ring (Fig. 12) is believed to be maintained against collisional diffusion by the gravitational perturbations of the 20-km-diameter satellite, Pan, orbiting within it; radial oscillations of characteristic azimuthal wavelength ~0.7° seen along the edges of this gap are also attributable to this small satellite. Density and bending waves are seen throughout the rings—these are radial and vertical disturbances that wrap around the planet multiple times on tightly wound spirals (Fig. 16). Such waves are created by gravitational resonances too weak to open gaps; features due to Mimas, Janus, Epimetheus, Pandora and Prometheus have been known since the *Voyager* flybys. *Cassini* has identified numerous additional examples, including ones due to tiny Atlas and Pan (Fig. 19). With few exceptions, the best understood features in Saturn's main rings are due to gravitational resonances.

There has been some success at linking narrow rings to nearby shepherding satellites. At Uranus, it is clear that the particles within the ε ring are shepherded in their movement around the planet by the gravitational perturbations of two small satellites on either side of it, Cordelia and Ophelia. At Saturn, the F ring (Fig. 13) is flanked by two small satellites, although the larger and more massive of the two is closer to the ring, in contrast to expectations. And the action of a single satellite, Galatea, may confine Nepune's Adams ring and its intriguing arcs (Fig. 10). A resonance with Galatea forces a coherent 30-km amplitude radial distortion to travel through the arcs at the orbital speed of the satellite. This particular resonance also seems capable of confining the arcs both in radius and azimuth—one satellite doing double duty—although it alone may not be sufficient to explain the observed configuration of arcs. Small, kilometer-sized bodies embedded within the ring or arcs might assist Galatea in arc confinement as well as slow the rapid retreat of the arcs from the satellite. Unfortunately, satellites of this size are well below the detection limit in Voyager images. If smaller satellites are discovered in close proximity to this or other narrow features, then dense narrow rings may be, fundamentally, not very different from Saturn's dense broad rings. If, however, the uranian and neptunian rings maintain their narrowness in some other way, then their internal dynamics, like their appearances, may be quite distinct from their broad saturnian cousins.

4.2.2 RADIATION AND ELECTROMAGNETIC FORCES

Small dust grains accumulate electric charges in planetary magnetospheres by running into trapped electrons and ions and by interacting with solar photons. These grains can be affected by electromagnetic forces that arise from

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their motion relative to the spinning magnetic field of the host planet. Additionally, the absorption, reemission, and scattering of solar photons by dust grains impart small momentum kicks to orbiting material that can, over long enough times, cause significant orbital changes. These are the two dominant nongravitational forces active in ring systems. Additionally, much weaker drag forces arising from the physical interaction of dust grains with photons, orbiting ions and atoms, and other smaller dust grains cause orbits to slowly spiral into the planet or, in some cases, to slowly drift away from it. All of these nongravitational forces, acting in concert with gravitational ones, cause long-period eccentricity and, to a lesser extent, inclination oscillations in faint dusty rings where collisions are rare. These effects are seen most clearly in Saturn's E ring, whose icy particles are thought to be ejected from newly discovered volcanic vents on the satellite Enceladus (Fig. 18). Despite this single source, the perturbation forces spread ring material hundreds of thousands of kilometers inward and outward to form a broad, relatively flat, and nearly featureless structure known as the E ring, the largest ring in the Solar System (Fig. 2).

Jupiter's magnetic field is ten times stronger than that of any other planet, and so it is no surprise that its dusty ring components are all strongly affected by electromagnetic processes. Because the magnetic field is also asymmetric (unlike Saturn's), electromagnetic resonances analogous to satellite gravitational resonances discussed above are active at particular locations in Jupiter's ring. For example, as discussed previously, ring particles are created by impacts into the four small satellites that populate the inner jovian system, and these grains subsequently evolve inward. A pair of electromagnetic resonances await the evolving grains, acting as sentinels guarding the approach to the King of the Planets. The first, at the inner edge of the main ring, imparts inclinations to the ring particles and creates the vertically extended jovian halo (Fig. 4). The second imposes still higher inclinations at the inner edge of the visible halo.

Other dusty rings at Uranus and Neptune may behave similarly; the upcoming 2007 uranian ring plane crossing will provide an excellent opportunity to search for faint vertically extended structures.

4.2.3 EXTERNAL MASS FLUXES

Yet another possibility for externally influencing ring structure arises from the redistribution of mass and angular momentum caused by meteoroid bombardment of the rings. Saturn's rings present a large surface area—twice that of the planet itself—to the hail storm of interplanetary debris raining down on them. The total mass falling onto the rings over billions of years may be greater than the mass of the rings themselves; this process is therefore likely to be a major contributor to ring erosion and modification. Numerical simulations of the process indicate that sandblasted ring particles should drift inward by up to several centimeters per year. This rate depends sensitively on the amount of material impacting the rings, a quantity that is presently poorly constrained. Potentially, though, the entire C ring of Saturn could decay into the planet in $\sim 10^8$ years. Because the ejecta from each impact is distributed preferentially in one direction, meteoroid bombardment provides a mechanism for altering radial structure. This is especially true when the initial radial distribution of mass is grossly non-uniform, such as near an abrupt and large change in optical depth. The shapes of the inner edges of the A and B rings and features near them can be explained roughly by this process and may take as little as $\sim 10^7$ to 10^8 years to evolve to their currently observed configurations. These results hint that other structural features in ring systems may also be explainable by this process.

The impacts of micrometeoroids onto Saturn's rings have also been proposed as the first step in the production of spokes, those ghostly patchy features in the B ring that come and go while revolving around Saturn (Figs. 14 and 15). Spokes are almost certainly powder-sized ice debris that have been lifted off bigger ring particles; the elevation mechanism is believed to involve electromagnetic forces acting on charged dust grains. Details of spoke formation and evolution depend on Saturn's orbital period, a fact that strongly indicates the importance of electromagnetic interactions between the dust and the planet's magnetic field.

5. Ring Origins

Three distinct scenarios have been suggested for the origin of rings: (1) rings may be the inner unaccreted remnants of the circumplanetary nebulae that ultimately formed the satellite systems surrounding each planet; (2) they may be the remnant debris from satellites that have tidally evolved inward toward the Roche zone, were completely disrupted by cometary or meteoroid impacts, and then spread quickly into a ring system, replete with small embedded satellites; or (3) they may be the result of the disruption of an icy planetesimal in heliocentric orbit that strayed too close to the planet, was torn apart by planetary tides, and subsequently evolved into a ring/satellite system. We discuss the pros and cons of each of these possibilities in turn.

Saturn's main rings, far more massive than all other ring systems put together, would appear to have the best chance of being primordial. Several lines of circumstantial evidence, however, indicate that this may not be so. First, the presence of the large moonlets Pan and Daphnis in the Encke and Keeler gaps shows that a certain amount of accretion would have to have occurred in a primordial disk. Why would the larger of these moons be closer to the planet where tidal forces limiting accretion are stronger? Additional evidence against primordial rings rests on the calculation of the rate of separation expected in the orbits of satellites and ring particles locked in gravitational resonance, e.g., the predicted recession of the small ring shepherds from the A ring due to their resonant interactions with ring particles. Simple inverse extrapolation of these rates brings the nearest of these satellites to the edge of the rings roughly 10^7 years ago. Estimates for the lifetime of all rings against erosion and darkening by micrometeoroid impacts yield similar time scales. On the basis of these arguments, ancient, and certainly unchanging, ring systems seem unlikely. Certain aspects of these theoretical models, however, are extremely uncertain and additional, as yet unidentified, processes may also be active. Thus, arguments both for or against ancient, but ever-changing, rings are still inconclusive.

The second possibility is somewhat more appealing at first glance. The large number of satellites presently orbiting each of the giant planets, and the ever-increasing discoveries of icy planetesimals found in the Kuiper Belt (a suspected source of planet-crossing bodies), indicate sufficient fodder for ring creation. The interpretation of the crater populations on the surfaces of outer Solar System satellites suggests that satellite disruption must have been a common event in the past. [*See* KUIPER BELT.] Jupiter's ring cleanly fits the second scenario, as the ring components are far less massive than the embedded satellites and, as far as we know, all structures are consistent with debris launched from these four objects. The individual particles in dusty rings, in general, have ages of well under a million years, as a variety of processes remove dust grains on these or appreciably faster timescales. Thus they must be replenished from known or unseen sources. At Uranus and Neptune there is also sufficient mass, even today, in ring-region satellites to create the present ring systems. But the possibility of creating Saturn's massive ring system in the recent past from satellite disruption is rather low, as Mimas-sized bodies near the Roche zone are nonexistent now and probably were rare in the past.

Finally, the fate of Comet Shoemaker-Levy 9, captured by Jupiter and torn into a long train of fragments, led to renewed interest in the idea of a ruptured planetesimal origin for rings. This is the weakest of the three scenarios, as it is expected that most of the debris from such an event would escape the planet or evolve to collide with it or its larger satellites before mutual collisions amongst the debris itself could damp the system down to a flat circular ring. Furthermore, the frequency with which large icy planetesimals pass near planetary cloudtops is too low to make tidal disruption a plausible scenario. Thus youthful rings appear more likely at Jupiter, Uranus, and Neptune, while the origin of Saturn's massive ring system remains an unsolved mystery.

6. Prospects for the Future

Further improvements in ground-based observing facilities and instrumentation can be expected in the future, but the most spectacular advances in the study of rings will certainly come when the vast quantity of data returning from the *Cassini* spacecraft is fully digested. New saturnian satellites well below the *Voyager* detection limit ($r \sim 6$ km), both internal (Daphnis) and external (Methone, Pallene) to the rings have already been detected (Fig. 2). High-resolution maps of the rings' composition and radial structure, and detailed studies of time-variable features are currently being undertaken. The figures in this chapter highlight some of the exciting first discoveries.

The ring systems of today offer invaluable insights into the processes operating in primordial times in the flattened circumsolar disk that ultimately formed the solar system. Yet almost all the results on the internal workings of Saturn's rings that will come from *Cassini*—the collisional frequency and elasticity of ring particles, the kinematic viscosity, and self-gravity—will be made on the basis of inference, as direct imaging of ring particles and their interactions will be impossible from the trajectory that *Cassini* will follow through the Saturn system. [*See* THE ORIGIN OF THE SOLAR SYSTEM.]

For this reason, it is likely that in the not-too-distant future we will dispatch, to follow in the wake of *Cassini*, small spacecraft capable of hovering over the rings of Saturn or orbiting within one of the large ring gaps. Views of the rings from these unique vantage points will capture individual ring particles—large and small—in the act of colliding, chipping, breaking, and coalescing. Observations like these will give planetary scientists an unprecedented opportunity to view details of these key processes that were probably also active in the solar nebula disk from which our solar system formed.

To follow up on our initial exploration of the outer solar system, orbiter missions to Uranus and Neptune are sorely needed. These missions, currently in the early planning stages, will raise our knowledge of distant ring systems up to the level of those of Jupiter and Saturn and allow meaningful comparisons to be made. Why does Saturn alone have a massive resplendent ring system? What new rings await discovery at Uranus and Neptune? Closely monitoring the timeless ballet danced by planetary rings and their satellite companions will ultimately reveal the underlying music to which they move. Perhaps one day in the far future, a cometary impact may rip a small satellite of Uranus or Neptune asunder, wreathing one or the other of the blue planets in a beautiful broad ring system to rival Saturn's.

In the next few decades, entirely new ring systems are likely to be detected around extrasolar giant planets; these will almost certainly show new forms and provide new hints about the dynamical forces that shape these elegant structures. Future generations of planetary ring enthusiasts will have much to look forward to and can expect many further surprises.

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