I

INTRODUCTORY MATERIAL

1

Space Age Studies of Planetary Rings

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1.1 INTRODUCTION: THE ALLURE OF THE RINGED PLANETS

One of the most enduring symbols of space exploration is a planet surrounded by a ring. This symbol inspires a celestial context: nothing on Earth is like it. It has been a wonderful surprise that the ringed planets are just as beautiful and scientifically compelling seen close up. Furthermore, the ringed planets are not just objects of beauty, but complicated physical systems that provide a local laboratory and analogy for other cosmic systems like galaxies and planet-forming disks. For a general review, see Esposito (2014). For more details, see the individual chapters that follow in this book.

We now know that planetary rings, once thought unique to the planet Saturn, exist around all the giant planets. These rings are not solid objects, but are composed of countless particles with sizes from specks of dust to small moons. For each planet, the rings are quite different. Jupiter's ring is thin and composed of dust-like small particles. Saturn's rings are broad, bright, and opaque. Uranus has narrow, dark rings among broad lanes of dust that are invisible from Earth. Neptune's rings include incomplete arcs restricted to a small range of their circumference. All rings lie predominantly within their planet's Roche limit, where tidal forces would destroy a self-gravitating fluid body. They are also within the planet's magnetosphere and, in the case of Uranus, they are within the upper reaches of the planetary atmosphere.

The common occurrence of ring material around the outer planets is one of the major scientific findings of the past 40 years. The new ring systems were discovered by both spacecraft and ground-based observers, often surprising us by contradicting our expectations. The rings' appearance and composition differ among the various planets, and likewise within each ring system. The broadest set of rings and the most identified processes are found around the planet Saturn, which has been scrutinized by the US/European Cassini space mission since 2004.

The detailed views from spacecraft, ground telescopes, and the Hubble Space Telescope show the following structural features in planetary rings: ring thickness considerably greater than the average particle size; dark lanes, gaps, and other density variations; eccentric and inclined rings; sharp edges; azimuthal brightness variations, arcs, and clumps; waves and wakes; and incomplete, kinked, and apparently braided rings. We still lack good explanations for much of this dazzling variety of phenomena, although many of these features have been explained by gravitational interactions between the ring particles and nearby moons.

Beyond the interactions with moons (many of which were likewise discovered by close-up pictures from spacecraft), the ring particles interact with the planet's magnetosphere via charging, plasma drag, and forces from the planet's own magnetic and electric field. Electrostatic effects lift small particles from the surface of the larger ring particles to create the dark radial lanes, called spokes, that are seen in the Voyager Saturn and Cassini pictures. Ring particles suffer a gas drag from the extended planetary atmosphere that causes them to spiral inward to destruction.

Ring particles come in a broad range of sizes. Their size distribution extends from submicron dust, through meter-sized particles, to small embedded moons like Saturn's moons Pan and Daphnis, about 10 km in radius. Theoretical expectations and some data support the idea that the particles in a ring will segregate in size, both radially and vertically.

What are ring particles made of? The ring composition is well known only for Saturn. Spectroscopic, occultation, and neutron measurements all imply that Saturn's rings' particles are almost entirely water ice. They are bright like the surfaces of Saturn's inner satellites. For the other ring systems, the particles resemble the nearby small moons and probably contain significant silicate and, in the case of Uranus and Neptune, possible carbonaceous material. Even in the Saturnian rings, color and spectral variations indicate compositional differences between different parts of the rings. Some of these differences may be primordial: others arise from interactions with the environment, including meteoroid bombardment.

Radio occultations at multiple wavelengths have provided size information for the Saturn and Uranus rings in the range of roughly 1 cm to 10 m. Information on smaller particles is from photometry and differential opacity in stellar occultations. Cassini's Cosmic Dust Analyzer has directly sampled the smallest ring particles. The broad ring-particle size distributions are similar to those arising from catastrophic fragmentation of small solid bodies.

We have a first-order understanding of the dynamics and key processes in rings, much of it based on previous work in galactic and stellar dynamics. The rings are a kinetic system, where the deviations from perfect circular, equatorial motion can be considered as random velocities in a viscous fluid. Unfortunately, the models are often idealized (for example, treating all particles as hard spheres of the same size) and cannot yet predict many phenomena in the detail observed by spacecraft (for example, sharp edges). Collective effects can also give rise to unexpected structures. The latest Cassini data show spectacularly that the rings do not behave like a simple fluid.

The rings show many youthful features: Saturn's ice is bright and relatively undarkened by meteoritic dust, the Uranus rings are narrow, Neptune's arcs are constrained to a small range of longitude, and Jupiter's ring particles are so small that they will be dragged away into the planet's atmosphere in a thousand years or less. The angular momentum that is now being transferred between rings and the nearby moons through density waves should have caused them to spread much further apart than they currently are. Further, the small moons discovered by Voyager could not themselves have survived the flux of interplanetary meteoroids for the age of the solar system. In much less time, these small moons would be shattered by an impacting object. These impacts not only destroy the moons; they can also recreate the ring systems. The new rings would gradually spread and eventually be ground to dust. Shattered moons can re-form, to provide material for future rings. Data from Cassini's observations indicate the moons not only sculpt the rings' structure; they also provide the reservoirs for past and future ring systems, and possibly trigger new structures forming now.

This unexpected range of phenomena seen in planetary rings gives some insight into the processes in other flattened astrophysical systems. The processes we now observe in planetary ring systems parallel those that occurred at the time of the origin of the planets. Clearly, the rings are not now accreting to form planets, as the original planetesimals did. However, many processes that are occurring now in rings resemble those in the solar nebula, particularly interactions between the disk and embedded protoplanets. Models that explain the present processes in rings can be compared in detail to ring observations, allowing testing and refinement that is no longer possible for the early solar system. In 2009, the Cassini space mission observed the Sun setting on the rings, which occurs every 15 years, at Saturn's equinox. This unique viewing perspective allowed us briefly to see structures never before seen. Cassini continues to observe Saturn's rings until the mission's planned end in 2017.

Fortunately for Cassini, the spacecraft has no plans to crash into the rings. Even small particles of 1 mm or so can be deadly, but they are likely to be rare outside the visible rings. Unfortunately, this means that we will attain no close-up views of individual ring particles. NASA has considered plans for a future "Ring Observer" mission that would come close enough to the rings to hover and capture pictures of the individual particles. Such views would provide spectacular "ground truth" for the remote sensing from flyby and orbiter spacecraft.

1.1.1 Studies of Planetary Rings 1610–1976

The possibility of rings surrounding the planets was not imagined by the ancients. Even the possibility that the planets possess moons was a surprise to Renaissance intellectuals. This latter finding was one of the first discoveries made by Galileo with the newly invented telescope in 1609, when he turned his view to Jupiter and discovered it to be accompanied by the four small objects Io, Europa, Ganymede, and Callisto.

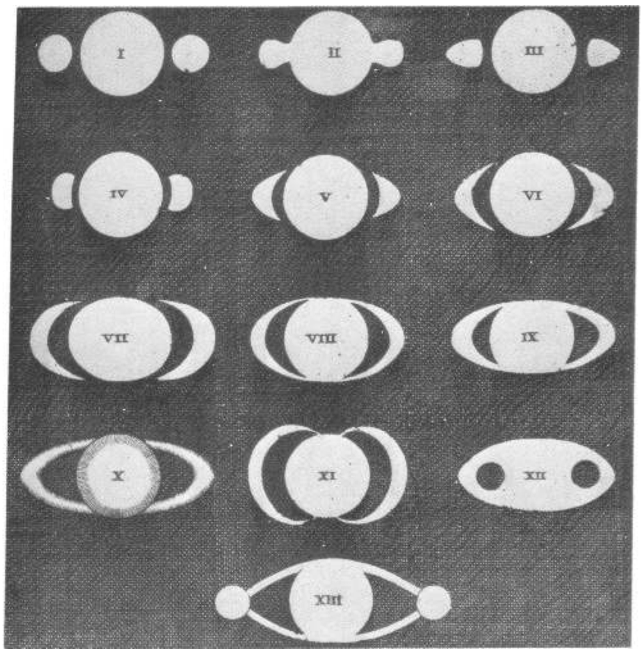

Figure 1.1 Seventeenth-century drawings of Saturn (from *Systema Saturnium*, 1659). I, Galileo (1610); II, Scheiner (1614); III, Riccioli (1641 or 1643); IV–VII, Hevel (theoretical forms); VIII, IX, Riccioli (1648–50); X, Divini (1646–48); XI, Fontana (1636); XII, Biancani (1616), Gassendi (1638–39); XIII, Fontana and others at Rome (1644–45). Riccioli made a drawing in 1646 rather like XI but less distorted. (Photographed from the copy of *Systema Saturnium*, © The Trustees of The British Museum.)

In 1610, Galileo turned his telescope to Saturn. With his imperfect optics, it seemed that the planet had a giant moon to either side. But these "moons" were unlike the Jupiter satellites he had found previously: they apparently remained stationary. See Figures 1.1 and 1.2 for early drawings that try to capture Saturn's puzzling behavior. In 1656 the Dutch astronomer Christiaan Huygens deduced the correct explanation and published it as a Latin anagram. Figure 1.3 shows a modern version of Huygen's solution. The flattened rings appear differently at each Saturn season, as viewed from the Earth; in fact, they vanish when the Earth passes through the plane of Saturn's equator. This ring-plane crossing phenomenon occurs about every 15 years, approximately at the equinoxes on Saturn. During 1995 to 1996, the Hubble Space Telescope observed the ring plane crossing events (see Figure 1.4). The main rings of Saturn are so thin that no light reflected from them at the exact moment of crossing has ever been observed, even by Hubble. Hubble saw mainly the reflection from Saturn's F ring, equivalent to a layer about 1.5 km thick (Nicholson *et al.*, 1996). Cassini close-up observations during the equinox of 2009 confirm that the rings are flat and thin, but with occasional excursions up to a few kilometers in perturbed regions.

Huygens argued that his telescope was superior to those with whom he disputed, but this was not justified. In fact, his contemporaries had observed the same phenomena but had not interpreted them as he did. The difference was thus not in seeing the rings, but in *perceiving* them.

It is clear that Huygens was drawn to the correct solution as much (or more) by his philosophical conceptions as by his own

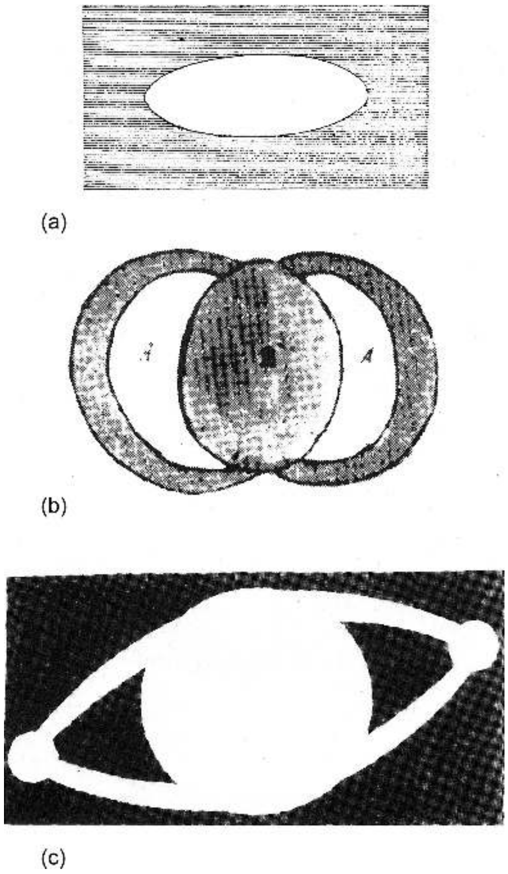

Figure 1.2 Drawings of observations by (a) Pierre Gassendi (1634), (b) Francesco Fontana (1638), and (c) Fontana (1645). Originals in *MSS Galileiana* 95, f. 81r, Biblioteca Nazionale Centrale, Florence, Italy. (By concession of the Ministero per i Beni e le Attività Culturali della Repubblica Italiana.)

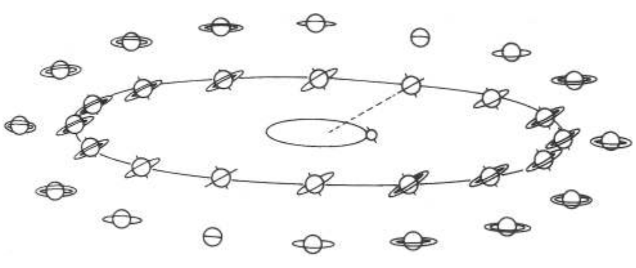

Figure 1.3 Cartoon views of Saturn and its rings over one Saturnian orbit according to Huygens' model (de Pater and Lissauer, 2010, after Huygens, 1656). The inner ellipse represents the Earth's orbit; the outer ellipse represents Saturn's orbit. The dashed line is the view from Earth. The outer drawings give the appearance of the rings as seen from Earth. (Reprinted with the permission of Cambridge University Press.)

observations (van Helden, 1984). In the more recent history of planetary ring studies, a similar situation is evident: repeatedly we have found we need to overcome our preconceptions to understand the rings. Particularly, there is a need to reverse the model of Saturn's rings that persisted up until the late 1970s as simple, circular, unchanging, equal-sized bodies orbiting the planet. Spacecraft and ground-based observations have forced

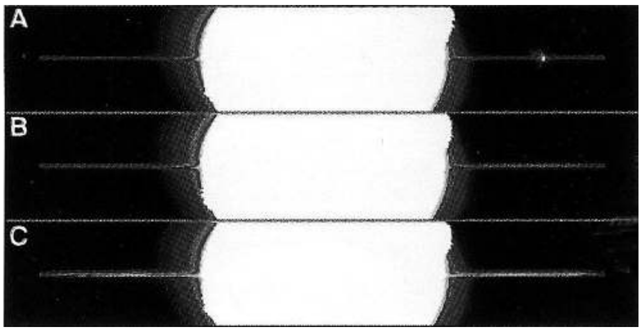

Figure 1.4 A sequence of Hubble images at 0.89 μm obtained on August 10, 1995, as the Earth crossed Saturn's ring plane, at (A) 20:12, (B) 21:49, and (C) 23:42 UT. Each frame is a composite of two images, processed to remove cosmic rays and small satellites. Dione is visible 17 arcsec west of Saturn in (A). The planet's disk is heavily saturated in these 300-s exposures. North is up, and east is to the left in all figures (from Nicholson *et al.*, 1996). (Reprinted with permission from *Science*, **272**, 509–15. Copyright 1996, American Association for the Advancement of Science.)

us to drop the simple models and embrace a much more complicated and active view of planetary rings. The rings have changed between the Voyager and Cassini missions, both in small particulars and also as we perceive them. Greenberg and Brahic (1984) note that this has forced the study of planetary rings to be dynamic and evolving: like the rings themselves! The observations continue to provide a sharp incentive, challenging us to extend our thinking and drop our preconceptions to truly understand the nature and history of planetary rings.

1.1.2 Discovery of the Uranian Rings

This discovery (Elliot *et al.*, 1977; see Figure 1.5) was only the first of many surprises over the five years beginning in 1977. Other observers quickly confirmed the findings, and the combination of multiple observations determined the widths and locations of the Uranian rings. Not only were Saturn's rings no longer unique, but the new Uranian rings were surprisingly quite different: they were narrow with sharp edges, and some rings were eccentric.

1.1.3 Pioneer and Voyager Discoveries

At this same time, the first spacecraft were on their way to Saturn: Pioneer 11 had flown by Jupiter in 1974 and would reach Saturn in 1979; Voyager 1 and Voyager 2 would fly by Saturn in 1980 and 1981 after gravity assists from Jupiter in 1979.

The next surprises were seen by Voyager at Jupiter in 1979. Six years earlier, Pioneer had detected an absence of radiation belts near the planet that could be explained by their being erased there by absorption due to a Jupiter ring. After some argument, Tobias Owen convinced his colleagues and the Voyager project management to invest precious minutes as the Voyager 1 spacecraft passed over the Jupiter equator to stare at apparently blank space in the direction of a possible ring. That Voyager image showed a new ring!

When Voyager 2 followed only months later, it was reprogrammed to snap a small number of images, which showed the new ring to be yet more different from the expectation based on

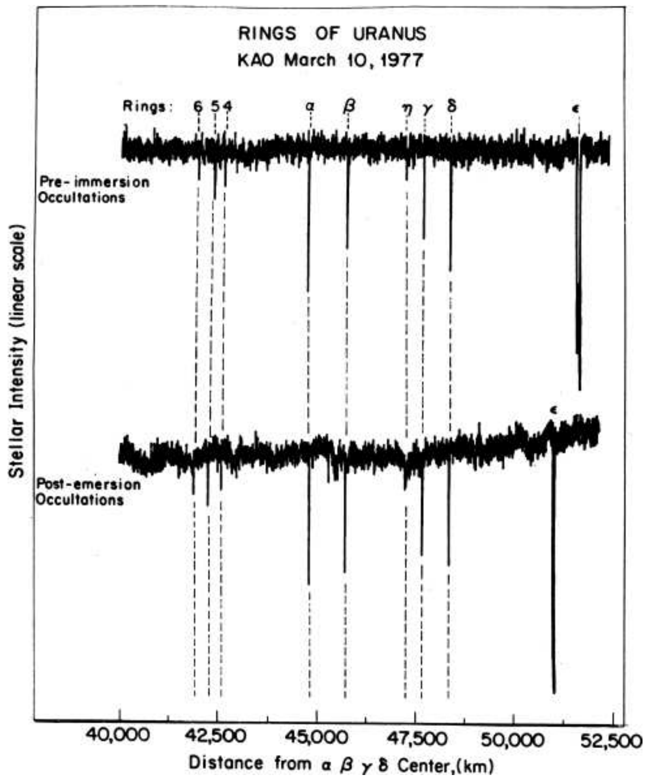

Figure 1.5 Occultations by the rings of Uranus. The pre-immersion and post-emersion occultations by the rings of Uranus observed with the Kuiper Airborne Observatory on March 10, 1977, have been plotted on the common scale of distance from the center of Uranus in the ring plane. Occultations corresponding to the nine confirmed rings are easily seen. Most (if not all) of the low-frequency variations in the lightcurves are due to a variable amount of scattered moonlight on the telescope mirror (from Elliot, 1979). (Reprinted with permission, from the *Annual Review of Astronomy and Astrophysics*, Volume 17, © 1979 by Annual Reviews www.annualreviews.org.)

Saturn's rings – it was broader than the Uranian ring system, but ethereal, less opaque than Saturn's main ring by a factor of a million.

Later that same summer of 1979, Pioneer 11 became the first spacecraft to reach what we had called *the* Ringed Planet just a few years before. It provided discoveries of new rings, F and G, around Saturn.

The Voyager flybys showed close-ups of the new rings D, E, F, and G; abundant structure in the main rings; waves, wakes, and scalloped edges; and numerous small moons. Two of these new moons, now known as Pandora and Prometheus, were on either side of Saturn's F ring, apparently confirming the "shepherding" theory, that the ring is held in place by gravitational interactions with these small moons.

One of the most remarkable discoveries of the Voyager encounters was the numerous waves visible in Saturn's rings. The cameras, the radio science investigation, the photopolarimeter experiment, and the ultraviolet spectrometer all saw ripples passing through the rings, each excited by the gravity of nearby moons. Each wave was generated at a location in the rings where the natural orbital motions of the particles were in a resonance with the motion of a nearby moon. Remarkably, these spiral waves could be explained by the same theory developed earlier to explain the arms of spiral galaxies. These waves would later provide estimates of the rings' total mass, random velocities, thickness, and age.

1.1.4 Cassini at Saturn

The Cassini orbiter has been orbiting Saturn since 2004, with the mission extended until 2017, when Saturn is at solstice. In 2009, Cassini observed the rings of Saturn at equinox, when they lie parallel to the Sun's rays. At that time, any vertical variations or larger objects catch the light of the Sun and shine like a mountain peak just after sunset. The shadows are long and much bigger than the features that cast them: these two effects allowed the Cassini instruments to observe phenomena that were much too small to resolve before.

Cassini observations confirm that the ring particles are composed of mostly pure water ice, with some contaminants. The particles cover a range of sizes from dust to small moons. Some small embedded moons were discovered by noticing a propeller-shaped effect on nearby ring material. Cassini showed that the ring particles form temporary elongated aggregates tens of meters across called "self-gravity wakes." The rings are highly dynamic, with some changes apparent since the Voyager flybys. A few aspects of ring structure can even change in a matter of days or weeks; we literally see the rings change before our eyes! The rapid changes are hard to reconcile with ancient rings as old as the solar system, unless some renewal or recycling is occurring. Cassini can directly measure the rings' mass and the nature of the interplanetary particles that continually bombard it. This will help decide if the rings are remnants of the Saturn nebula or fragments of a destroyed moon or comet.

Cassini has focused its study on many of the dynamic structures that change over time scales of hours, months, and years. Small-scale structure is apparent: one example is self-gravity wakes, another is the surprising phenomenon of overstability (see Section 1.5.3), and we also detect individual objects that are only 100–1000 m in dimension. Vertical structures of kilometer extent are created by small moons on inclined orbits. Satellites open gaps, some extending just part of the circumference to produce the propeller structures. High phase angle images show dusty rings that distort under the Sun's influence. Larger objects embedded in the F ring that are only about a kilometer in size stir the ring up, with the objects occasionally colliding to release jets of dust. In perturbed regions, the ring particles are agitated, exciting higher velocity, but also temporary aggregation. The ring spectra and photometry clearly show the effects of this stirring, with bright "haloes" surrounding the strongest density waves. There is evidence that the rings of Saturn are older than Voyager suggested, going back to the formation of the solar system or perhaps to the era of late heavy bombardment that followed, about 3.9 billion years ago. Because the rings appear to be nearly pure ice, this might require them also to be much more massive than previously thought, perhaps by a factor of ten. This would explain why they are not more polluted by the continuing infall of meteoritic material on the rings. There is some evidence for more massive rings based on self-gravity wakes seen by star occultations and from re-interpretation of some previous Pioneer 11 results. Further, simulation by Robbins *et al.* in 2010 of particle dynamics

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shows that the particles tend to clump, indicating that they are likely much more massive than estimated by Voyager and earlier results (e.g., Esposito *et al.*, 1983) that assumed the rings were homogeneous.

Conversely, measurements of the Cassini Cosmic Dust Analyzer confirm that the bombarding meteoritic flux is enough to darken the rings quickly: this implies that the rings are even younger or more massive than indicated by Voyager. Hedman and Nicholson's (2016) estimate of the low mass density of the B ring implies even less massive rings and consequently shorter ages.

When the aging spacecraft flies very close and even inside the rings, in its final proximal orbits, Cassini will systematically survey the Saturn ring system at multiple wavelengths, and provide ultra-high resolution by watching occultations of selected stars whose apparent motion nearly tracks the ring particle orbits. The extended mission will provide a complete seasonal coverage of the spokes.

At the end of the Cassini mission, before the spacecraft becomes a short-lived meteor in Saturn's atmosphere, many close-up views will be possible: during the last orbits Cassini speeds between the rings and Saturn at its closest approach. The spacecraft will pass so close to the rings that their gravity will change its orbit slightly, allowing us to directly measure, for the first time, the mass of the rings. This key result will test theories of the rings' age and evolution. If we find massive rings, they could be as old as the solar system, but possibly continually changing due to the random events they suffer.

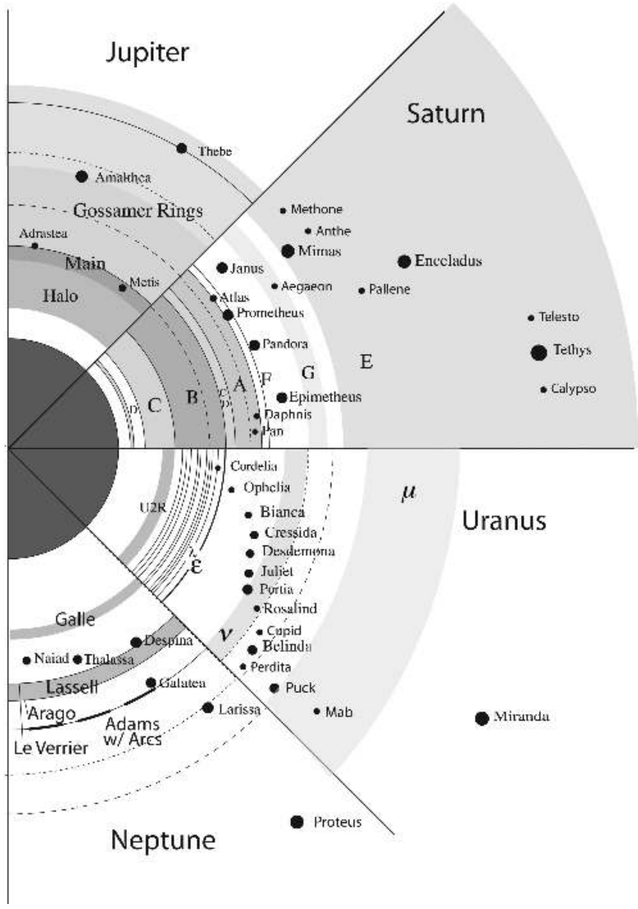

Figure 1.6 A comparison of the four planetary ring systems, including the nearby satellites, scaled to a common planetary equatorial radius. Density of shading indicates the relative optical depth of the different ring components. Synchronous orbit is indicated by a dashed line, the Roche limit for a density of 1 g cm^{-3} by a dot-dash line. (Figure courtesy of Judith K. Burns, from Burns *et al.* (2001), updated by Doug Hamilton and Larry Esposito. Dusty rings and circumplanetary dust. In *Interplanetary Dust*, ed. E. Grün, B. A. S. Gustafson, S. F. Dermott, and H. Fechtig. Berlin: Springer-Verlag, pp. 641–725; reproduced by permission of the publisher.)

1.2 DIVERSITY OF PLANETARY RINGS

Planetary rings are composed of a myriad of small particles, mostly orbiting inside the Roche limit of the giant planets. The *Roche limit* is the distance closer than which a fluid particle would be disrupted by tidal forces from the planet; at this limiting distance, the tides are just balanced by the self-gravity of the object (Weidenschilling *et al.*, 1984). An interesting exercise is to compare all the ring systems when normalized to the equatorial radius of each planet (see Figure 1.6, after Nicholson and Dones, 1991). This comparison clearly shows that the rings occupy a common location near the planets, overlapping with numerous small moons (called *ring-moons*) near the rings (Thomas, 1989). Table 1.1 gives the main properties of the ring systems.

1.2.1 Jupiter's Rings

Each ring system includes diffuse, tenuous rings, which Burns *et al.* (1984) have termed ethereal rings. Jupiter (Figure 1.7) provides the best studied example (see Chapter 6 by de Pater *et al.*). The Jupiter rings are composed of small dust grains released by the intermingled moons Adrastea, Metis, Amalthea, and Thebe. The densest ring of Jupiter, called the "main" ring, extends inward from the approximate location of Adrastea. Metis orbits closer, within the ring, and may be responsible for a lane of decreased brightness called the *Metis notch*. Much of the ring is composed of small, short-lived dust particles with size $1 \leq r \leq 15\,\mu$m. Above and surrounding the Jupiter main ring is a toroidal distribution of dust called the "halo" (Figure 1.8). Outside the main rings, we find two very faint "gossamer" rings (Figure 1.9), associated with the moons Amalthea and Thebe: Galileo observations confirm that each of these small moons are the source of the ring material inside them. The Thebe Gossamer ring extends slightly outward from Thebe's orbit, perhaps due to charging and discharging as they go in and out of Jupiter's shadow. The Jovian ring particles likely have silicate compositions, like the surfaces of the nearby moons. Even the biggest objects in it are all likely less than 1 km across.

1.2.2 Uranus' Rings

The rings of Uranus are narrow, with many eccentric or also inclined (see Chapter 4 by Nicholson *et al.*). They include dense rings with sharp edges unlike Jupiter's diffuse rings. Their composition is not known, but they cannot be dominantly

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Table 1.1. *Planetary rings characteristics*

	Location (width)	Optical depth	Dust fraction (%)	Power-law index	
Jupiter					
Halo	92 000–122 500 km	10^{-6}	100	?	12 500 km thick
Main ring	122 000–128 980	3×10^{-6}	$\sim$ 50(?)	$q \leq 2.5$	Bounded by Adras
Amalthea Gossamer	129 000–182 000	10^{-7}	100 (?)	?	2000 km thick
Thebe Gossamer	129 000–226 000	3×10^{-8}	100 (?)	?	4400 km thick
Saturn					
D ring	66 000–74 000	10^{-3}	5–100	?	Internal structure
C ring	74 490–91 983		<3	3.1	Some isolated ring
B ring	91 983–117 516	≤ 2.5	<3	2.75	Abundant structur
Cassini Division	117 516–122 053	0.05–0.15	<3		Several plateaus
A ring	122 053–136 774	$\sim$	<3	2.75–2.90	Many density wav
F ring	140 200 ($W \approxeq 50$ km)	0.1–0.5	>98	2–3	Narrow, broad cor
G ring	166 000–175 000	10^{-6}	>99	1.5–3.5	
E ring	180 000–1 200 000	10^{-5}	100		Peak near Encelad
Phoebe ring	60–400 R_s (Rs = 60 330km)	$2\text{x}10^{-8}$	100	?	The particles can
Uranus					
1986 U2R	37 000–39 500	10^{-4}–10^{-3}	?	?	Still unnamed
ζ	37 850–41 350	10^{-3}			
Dust belts	41 000–50 000	1–10^{-5}	?	?	Fine internal struc
6	41 837	0.3	<1	$q > 3.5$	
5	42 234	0.5	<1	$q > 3.5$	
4	42 570	0.3	<1	$q > 3.5$	
α	44 718	0.3	<1	$q > 3.5$	
β	45 661	0.2	<1	$q > 3.5$	
η	47 175	0.3	<1	?	
γ	47 627	2	<1	?	
δ	48 300	0.4	<1	?	
λ	50 023	10^{-3}	>95	?	Faint, dusty ring
ε	51 149	0.5–2.3	< 1	$2.5 < q < 3.0$	Adjacent to Corde
ν	66 100–69 900	$6\text{x}10^{-6}$	<1	?	Between Portia &
μ	86 000–103 000	$8\text{x}10^{-6}$	<1	?	Coincident with M
Neptune					
Galle	41 000–43 000	4–10×10^{-5}	?	?	
LeVervier	53 000 ($W = 10$ km)	10^{-2}	4–70	?	Adjacent to Despi
Lasell	53 000–58 000	1–3×10^{-4}	?	?	
Arrago	57 200 ($W = 100$ km)	?	?	?	
Adams	62 930 ($W = 50$ km)	10^{-2}	2–50	?	Adjacent to Galate
Adams arcs	62 930 ($W = 10$ km)	10^{-1}	4–70	?	

Sources: After Burns *et al.*, 2001; Nicholson and Dones, 1991; French *et al.*, 1991; Porco and Hamilton, 2007.

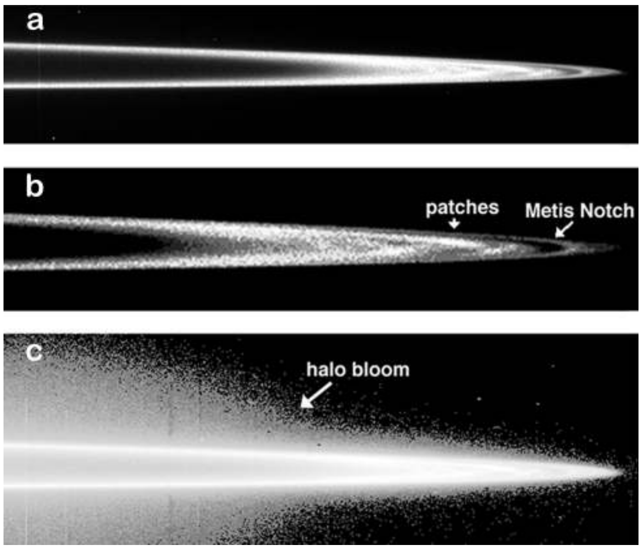

Figure 1.7 A Galileo view of the Jovian ring, showing both the main ring and the halo's outer parts, processed in three different ways to highlight various features. (a) Stretched to differentiate the main ring's diffuse inner periphery versus its much crisper outer boundary. (b) A stretch that emphasizes the patchy nature of the main ring's central region located just interior to a brightness dip associated with Metis' orbit. Features that are bright just above a horizontal line through the ansa tend to become dark just below the line, and vice versa. (c) By emphasizing fainter structures, the halo's development at the main ring's inner edge is revealed; it appears that the main ring itself is enshrouded in a faint cloud of material, the so-called "halo bloom," above and below. (From Ockert-Bell *et al.* (1999); reproduced with permission from Elsevier.)

water ice (like Saturn's rings) because their reflectivity is so low.

Uranus has ten narrow, sharp-edged rings, with eccentric shapes and small inclinations (Figure 1.10). Both the narrowness and sharp edges can be explained by the confining action of nearby moons, called "shepherds" for obvious reasons, since they act to keep a flock of ring particles in place. For the outermost of these narrow rings, the ε ring, these moons were photographed by Voyager in 1986 (Figure 1.11). For the other rings, the shepherds are still only hypothesized, not yet discovered. The eccentric shape may be explained by the rings' own gravity, or perhaps by particular characteristics of the ring particles' collisions at preferential longitudes. Lifetimes of the Uranian rings may be short, due to the inward drag from Uranus' extended atmosphere, and due to erosion by charged particles for the outer rings that form a second ring system discovered by Hubble in 2004.

The spaces between the Uranian rings are filled by broad, diffuse rings of small particles. These were only visible when Voyager 2 turned its camera back after passing Uranus and observed the backlit Uranian ring system. This phenomenon is characteristic of particles whose size is approximately the same as the wavelength of light they are seen with (see Section 1.3.1). The extensive sheets of material are likely debris knocked off from (yet undiscovered) small moons among the rings.

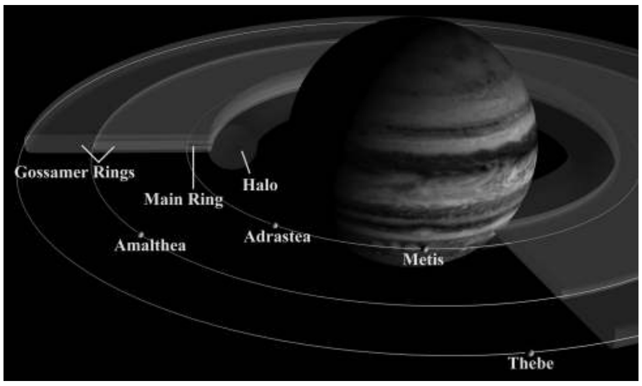

Figure 1.8 A cut-away view of the components of Jupiter's ring system is shown in relation to Jupiter and its small ring-moons. The innermost and thickest ring, shown as a torus, is the *halo* whose outer edge ends at the narrow and flat *main ring*. The main ring is circumscribed by the satellite Adrastea's orbit; it may be partly composed of fine particles knocked off Adrastea, and a somewhat larger moon Metis located about 1000 km closer to the planet. Thebe and Amalthea, satellites that are larger still, supply dust that forms the thicker, washer-like *gossamer rings*; the thicknesses of the gossamer rings are determined by the inclinations of these two satellite orbits. A very faint extension (not shown) of the outer gossamer ring reaches beyond Thebe's orbit. (From Ockert-Bell *et al.* (1999); reproduced with permission from Elsevier.)

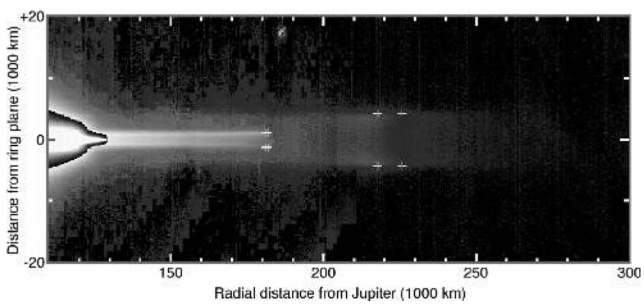

Figure 1.9 This mosaic of four Galileo images (416088922–416089045), taken through the clear filter (0.611 μm) at an elevation of 0.15°, shows the edge-on *gossamer rings* of Jupiter across phase angles of 177–179°. The halo and main ring are overexposed (solid white with a black outline; cf. Fig. 1.8) at left. White crosses mark the extremes of the radial and vertical motions of Amalthea and Thebe as caused by their eccentric and inclined orbits. Amalthea (whose position is roughly in mid-image) bounds one gossamer ring (its ring is the narrower and brighter strip extending to the right from the main ring); Thebe's ring is the thicker and fainter band reaching yet further right. A very faint outward extension to the Thebe ring is also apparent. This image has been enhanced logarithmically to show all the ring components; in reality the Amalthea ring is fainter by a factor of approximately 10 than the main ring, while the Thebe ring is fainter by a factor of 10 than the Amalthea ring. Note that each gossamer ring is densest along its vertical extremes, particularly the top strip of Amalthea's ring. The image has been expanded vertically by a factor of two to better show the rings' vertical structure. (From Burns *et al.* (2001) Dusty rings and circumplanetary dust. In *Interplanetary Dust*, ed. E. Grün, B. A. S. Gustafson, S. F. Dermott, and H. Fechtig. Berlin: Springer-Verlag, pp. 641–725; reproduced by permission of the publisher.)

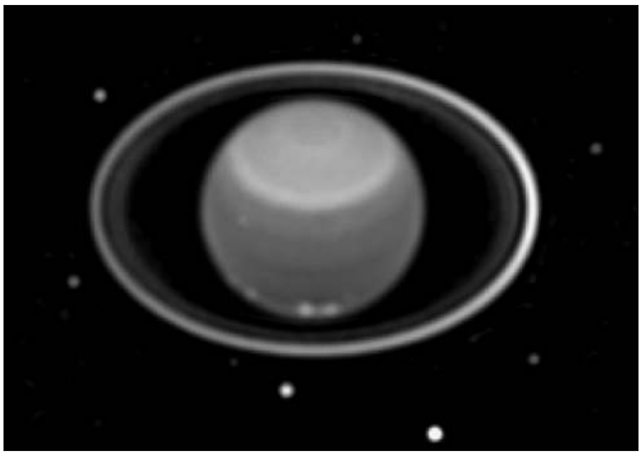

Figure 1.10 This image of Uranus shows the planet and some of its moons in infrared light. Its rings are clearly visible, and their orientation is unusual. Unlike most planets, whose poles point perpendicular to the Sun, Uranus and its rings rotate around an axis that is nearly in the plane of its orbit. (Courtesy NASA/JPL-Caltech.)

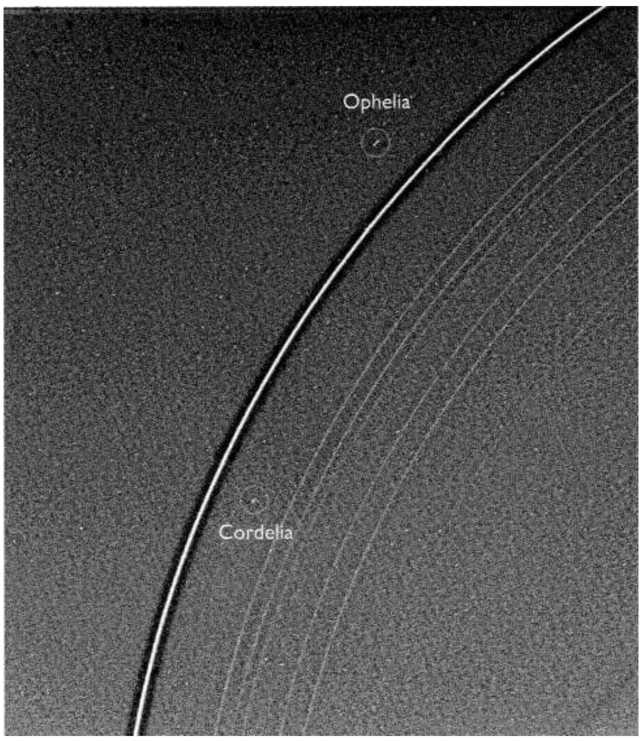

Figure 1.11 Cordelia and Ophelia, a pair of shepherding satellites on each side of Uranus ε ring, keep the ring particles in place through resonant gravitational forces. No other shepherds for the other rings were detected by Voyager 2 during its 1986 flyby. (Courtesy NASA/JPL-Caltech, from PIA01976.)

1.2.3 Neptune's Rings

Neptune's rings resemble the Uranus rings: they are primarily narrow, although further from the planet (see Chapter 5). The rings are named for individuals associated with the discovery of the planet Neptune. They exist inter-mixed with numerous small moons, further from the planet than the other known ring systems. Neptune was the first to show longitudinally incomplete rings, called ring "arcs."

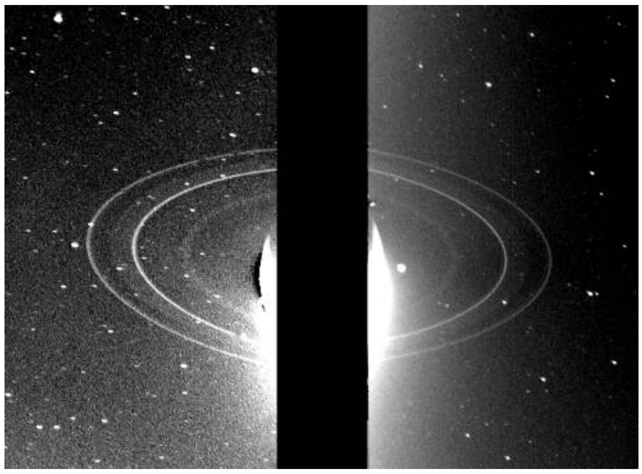

Figure 1.12 A pair of Voyager 591-second exposures (FDS 11446.21 and 11448.10) taken 1.5 hr apart through the clear filter of the Voyager wide angle camera at a phase angle of $\varphi \sim 134°$, that is, looking back toward the Sun (Smith *et al.*, 1989). The arc region of the outermost Adams ring was not captured in either image. PIA01997 (Courtesy NASA/JPL-Caltech.)

Neptune's ring system includes both broad and narrow rings (Figure 1.12). The rings are interspersed with four large satellites with radii of 30–80 km. The gravitational effects of the moon Galatea are clearly evident on the Adams ring (Neptune's largest), including possibly maintaining its hyphenated longitudinal structure. The first stellar occultation searches (which observed stars as they passed behind Neptune) were carried out from the ground. They gave inconsistent results: sometimes the starlight was blocked by a ring, and sometimes not. The proposed solution, that Neptune's rings are discontinuous, consisting of a series of incomplete "arcs," was spectacularly confirmed by Voyager 2 in 1989. These arcs are embedded in a diffuse complete ring almost invisible from Earth. These three main arcs are known as Liberté, Egalité, and Fraternité from the call to arms of the French Revolution. A fourth, later discovered arc, is known as "Courage," to be pronounced with a French accent on the second syllable. The brightest Neptune rings are named after the predictors and discoverer of the Planet Neptune: respectively, Adams, LeVerrier, Galle. Lassell and Arago are, respectively, British and French astronomers of the nineteenth century. William Lassell discovered Neptune's moon Triton. Arago measured the diameters of the planets, and as Director of the Paris Observatory, was embroiled in the controversy over credit over Neptune's discovery (Moore, 1995).

1.2.4 Saturn's Rings

Saturn's rings (see Chapter 3) are the biggest and brightest in the solar system (Figure 1.13). Calculations based on Voyager results indicate they contain as much mass as the moon Mimas, and they display all the phenomena found in the other three smaller ring systems. This includes gaps with embedded moons and ringlets, narrow rings, broad rings, ethereal rings,

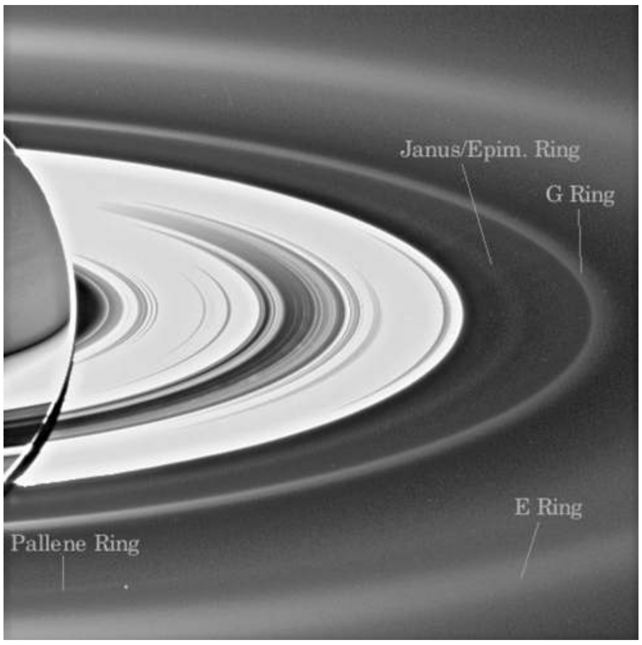

Figure 1.13 Saturn's ring system includes the diffuse rings. This image was taken with the Sun almost directly behind Saturn, showing the G ring, Pallene ring, E ring, and Janus/Epimetheus ring. Image number PIA08328 from the Cassini wide-angle camera on 15 September 2006. (Courtesy NASA/JPL/Space Science Institute.)

waves, wakes, and wiggles (see Section 1.4). Voyager saw time-variable radial dark lanes on the B (brightest, broadest) ring which were called "spokes"; density waves in the outer A ring; it saw the planet through the partly transparent C (crepe ring); and took close images of D, E, F, and G rings. The alphabetical naming of Saturn's rings, which follows the chronological discoveries of new rings, failed to keep up with the immense number of features seen by Voyager. Now, most ring features beyond the classical, pre-Voyager, rings are identified merely by their location. Ring D lies inside the brighter rings; ring E is a broad, tenuous ring centered on the moon Enceladus. The F ring is a narrow ring just outside the A ring. The G ring (Figure 1.13) is another narrow ring outside ring F: Cassini entered the Saturn system in an apparently empty area between the F and G rings in July 2004.

1.2.5 Dusty Rings

Dusty rings are tenuous and much more difficult to observe than Saturn's bright and dense rings. Nevertheless, dusty rings are interesting because their rich dynamics provide sensitive probes of their environment. The high surface-area-to-volume of dust-sized grains make them much more responsive to non-gravitational forces. Because of their low mass, several dust rings have changed substantially over timescales of years to decades. See Chapter 12.

1.2.6 Rings Around Asteroids

In 2013, the asteroid Chariklo was observed as it occulted a star, clearly showing the presence of two rings (Braga-Ribas *et al.*, 2014; see Chapter 7). The rings are 7 and 3 km wide. Chariko is technically classified as a centaur, a former Kuiper Belt object that orbits between Saturn and Uranus on an unstable orbit. The rings could have originated from an impact onto Chariklo, a collision between pre-existing moons, tidal disruption of a former moon, or cometary activity. Another centaur, Chiron, may also possess similar rings (Ruprecht *et al.*, 2015; Ortiz *et al.*, 2015). For more details, see Chapter 7.

1.2.7 Exoplanet Rings

Now that thousands of planets have been found around other stars, we can ask if any of these exoplanets have moons or rings. To date, neither has been confirmed. The technique of detecting planets as they transit in front of a star, which is the way most exoplanets have been found, could also provide signatures of their rings. If the exoplanets found so far resemble the outer planets of our solar system, they would be likely to possess ring and moon systems. Unfortunately, most other planet systems do not resemble ours, with giant planets that are found orbiting close to their stars. Because these "hot Jupiters" are so close to their parent stars, rings would be very hard to detect (see the analysis by Schlichting and Chang, 2011). Many of the ring systems would be edge on; particles in the rings would be quickly dragged away; and the regions close to the star are hot enough to vaporize ice and even melt rock. Mamajek *et al.* (2012) have explained the unpredictable flickering of the object J1407 by the orbit of an unseen planet with a ring system 200 times larger than Saturn's. This set of complex eclipses could not be the result of rings of a planet on a circular orbit. Simulations show that a prograde ring system would not be stable around a planet in an eccentric orbit, but that a retrograde ring could survive for 10 000 or more orbits (Rieder and Kenworthy, 2016). The authors plan to monitor this star for the next decade to confirm the possible presence of a Mars-size embedded moon and undulating waves of clumping material (Kenworthy, 2016).

1.2.8 Summary

In summary, planetary ring systems in our solar system show surprising variety. All are formed of immense numbers of small particles, individually too small to see, but collectively appearing as structures circling the giant planets. Particles range in size from dust to small moons. The composition of the ring particles, where we can determine it, resembles that of the nearby moons. Some rings are narrow, others broad; some eccentric, inclined, and partial; gaps in rings are empty, or occupied by small moons. The largest ring in the solar system was discovered by the Spitzer Space Telescope and named the "Phoebe" ring. Its particles likely orbit Saturn in a retrograde direction, as does Phoebe itself. The inwardly spiraling particles eventually hit Iapetus, darkening its leading side. Moons sculpt and confine rings, provide the sources and perhaps sinks for ring material. Saturn's rings encompass the phenomena seen in other rings and more.