

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. My own fascination with space began when first I saw Saturn and its rings through a small telescope. The study of planets and rings has become my lifelong vocation. What 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.

We now know that planetary rings, once thought to be unique to the planet Saturn, exist around all the giant planets. These rings are not solid objects, but 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 planets is one of the major scientific findings of the last 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.

In July 2004, the Cassini spacecraft began to orbit Saturn, with the mission planned to last four years. Just after the rockets fired to place Cassini into orbit, it took the closest, highest-resolution observations of Saturn’s rings. From a

distance of within 20 000 km, Cassini cameras and spectrometers returned spectacular data. Carolyn Porco of the Space Sciences Institute and leader of the camera team stated: “Our glistening golden-shrouded mechanical beast, with seven lonely years and billions of miles behind it, set its sights on a softly-hued, giant and dreamlike planet . . . We hasten soundlessly across a vast and solid sea of rippling waves, scalloped shores and tumbling rivers of frozen boulders, stones, pebbles all made of ice.” This is her description of the first Cassini high-resolution views of Saturn’s rings. Cassini took close-up pictures of new structures and new moons within the rings, measured the ring composition and its variation, saw evidence of dynamical phenomena indicating the gravitational interactions with nearby moons, and provided new findings about the ring evolution and history.

The detailed views from spacecraft, ground telescopes, and Hubble show a variety of structural features in planetary rings: vertical 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 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. Perhaps 100 to 1000 moons bigger than 1 km orbit each of the giant planets but were too small to be detected by spacecraft cameras. 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 amounts of 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 arrive 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 (e.g., treating all particles as hard spheres of the same size) and cannot yet predict many phenomena in the detail observed by spacecraft (e.g., 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 are now. 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 have been shattered by an impacting object. This realization provides a potential solution to the problem of young rings. 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 at Saturn equinox indicate that 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.

The Voyager flybys of the 1980s changed forever how we think about planetary rings. Cuzzi (1998) describes this as a "paradigm shift" that led us to the current conception of young and dynamic rings. The new and exotic phenomena seen close up by the Voyager spacecraft forced us to expand our conceptions and adjust them to the immediate reality. Unfortunately, the Voyager investigations were spotty in coverage, both in time and space. The Cassini spacecraft benefits from the

capability of experiments developed one generation later. And furthermore, from the long duration of its tour of the Saturn system, now extended to 13 years . . . , including the spectacular equinox, the moment when the Sun set on Saturn's rings in August 2009. Cassini's long mission allows us to address new questions and phenomena as they arise, and to follow up with deeper investigations. For example, some tantalizing bright clumps seen by Voyager in Saturn's F ring (Showalter, 1998) provided one example of targets for monitoring by Cassini's cameras. French *et al.* (2012) describe how the F ring is now spectacularly different from our Voyager view. Earlier predictions of small moons and self-gravity wakes within Saturn's rings have been confirmed by Cassini.

The Cassini capability exceeds that of Voyager in every area. The cameras resolve sub-kilometer structure in the rings. Multiday "movies" have tracked spokes, F-ring phenomena, and small satellites. More than 100 stellar and solar occultations define the radial and azimuthal structure in the rings, resolving features as small as a few meters. The Cassini experiments have observed the rings at wavelengths from the extreme ultraviolet to the mid-infrared. Radio occultations have defined the particle size distribution for particles with size from millimeters to tens of meters. The Cassini orbit provides a full range of observing geometry to catch the lit, unlit, shadowed, backlit, and full-phase (when the Sun is directly behind the spacecraft) rings. The combination of observing over this range of wavelengths and angles now gives us a much more complete picture of the vertical structure, particle temperatures, and particle shapes. Multiple observations have caught waves and wakes in action. The orbiter has measured the dust in the diffuse rings, around the rings, and in the bombarding meteorite population. The comprehensive Cassini payload allows us now to characterize the interactions of rings, atmosphere, ionosphere, and magnetosphere as well as ring-satellite relations and ring evolution. Joseph Burns of Cornell University said that "Cassini results may fundamentally alter our understanding of ring processes and even origins." The recent results of many Cassini scientists confirm this expectation. Cassini has now produced more than 300 papers about Saturn's rings.

I will emphasize that most rings are much younger than the solar system and that the likely explanation is that new rings are episodically created by the destruction of small moons. This idea is one example of how recent spacecraft observations have shown a larger role for catastrophic events in the history of the solar system. The role of singular events, like giant impacts, seems essential in explaining the history of planetary rings, placing ring history now in a class with the origin of the Earth's moon, the history of life on Earth, the rotation and tilt of the planets, and unique aspects of both Mercury and Pluto. Thus, the study of rings connects with similar rare and sudden processes like the formation of the Earth's moon and the demise of the dinosaurs.

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 are occurring now in rings that 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, just after summer solstice on Saturn.

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 (Canup and Esposito, 1997). 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.

This book briefly describes the rings in the solar system and some mathematical and physical approaches to understanding them. I will emphasize the variety of ring phenomena revealed in the last few decades from space and Earth observations. I address, in some detail, the recent history of rings and conclude with a discussion of the major open questions and future opportunities to learn about planetary rings. My presentation benefits and draws from previous reviews by Esposito *et al.* (1984), Esposito (1986), Esposito *et al.* (1991), Nicholson and Dones (1991), Esposito (1993), Porco *et al.* (1995), Cuzzi (1995, 1998), Burns *et al.* (2001), Esposito (2002), Dougherty *et al.* (2009), Cuzzi *et al.* (2010), Esposito (2010) and Tiscareno (2013b).

2

Studies of planetary rings 1610–2013

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. These bodies are now fittingly known as the Galilean satellites of Jupiter. The close-up investigations by space missions Pioneer, Voyager, Cassini, New Horizons and the Galileo space mission have revealed each satellite to be a unique world with its own history and geology. Galileo also turned his telescope to the Earth’s moon, where he discovered its mountains; to Venus, where he discovered its phases; and to the Sun, where he discovered sunspots. Each of these new findings undercut the classical ideas of an Earth-centered and perfect celestial universe: they provided basic support for the Sun-centered Copernican model, where earthly laws applied universally.

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. Furthermore, when he observed Saturn again in 1612, they had disappeared. Over the next decades, Saturn appeared in many different forms to the early telescopic observers. Their drawings give a bizarre array of inconsistent figures (see Figures 2.1 and 2.2) and further led to a variety of possible explanations (all incorrect) over the first half of the seventeenth century. Indeed, the nature of Saturn was one of the major astronomical controversies of that period. In 1656 the Dutch astronomer Christiaan Huygens deduced the correct explanation and published it as a Latin anagram, which when decoded and translated reads, “It [Saturn] is surrounded by a thin, flat ring, nowhere touching, and inclined to the ecliptic.” The modern view of Saturn’s seasonal changes can be seen in Figure 2.3. The flattened rings appear differently at each Saturn season, as viewed from the Earth; in

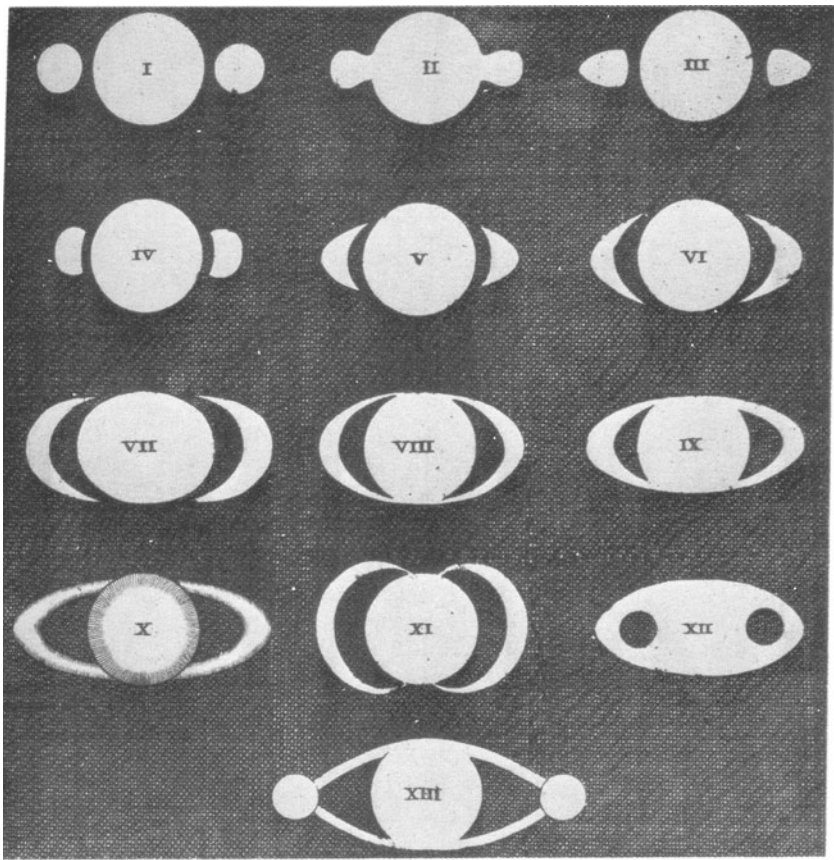


Figure 2.1 Seventeenth-century drawings of Saturn (from *Systema Saturnium*, 1659). I, Galileo (1610); II, Scheiner (1614); III, Riccioli (1641 or 1643); IV–VII, Hevel (theoretical forms); VIII, IX, Riccioli (1648–50); X, Divini (1646–48); XI, Fontana (1636); XII, Biancani (1616), Gassendi (1638–39); 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.)

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 2.4). 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,

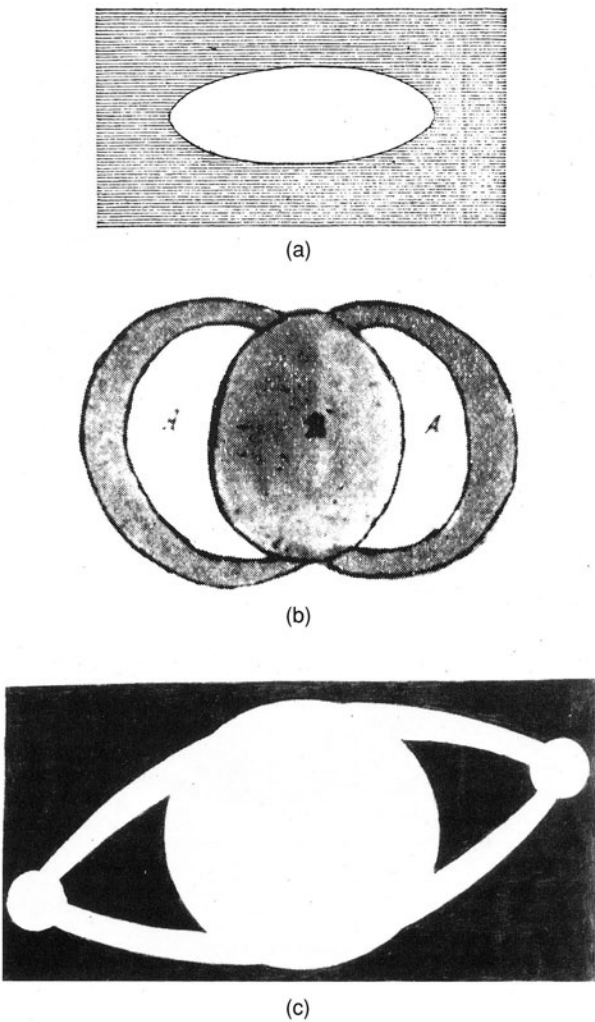


Figure 2.2 Drawings of observations by (a) Pierre Gassendi (1634), (b) Francesco Fontana (1638), and (c) Fontana (1645). Originals in *MSS Galileiana* 95, f. 81r, Biblioteca Nazionale Centrale, Florence, Italy. (By concession of the Ministero per i Beni e le Attività Culturali della Repubblica Italiana.)

but with occasional excursions up to a few kilometers in perturbed regions. (See Chapter 7.)

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 as he had but had not interpreted them as he did. The difference was not in seeing the rings, but in *perceiving* them. Huygens was a disciple of René Descartes, who developed the idea of a vortex as an explanation of motions in the

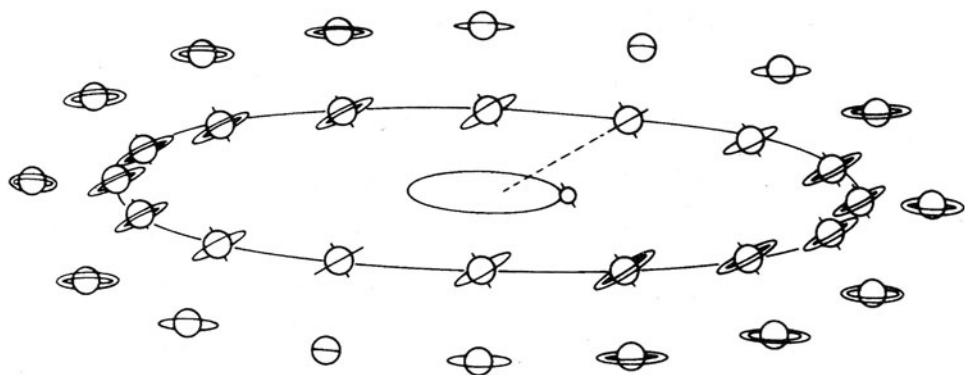


Figure 2.3 Cartoon views of Saturn and its rings over one Saturnian orbit according to Huygens' model (de Pater and Lissauer, 2010, after Huygens, 1656). The inner ellipse represents the Earth's orbit; the outer ellipse represents Saturn's orbit. The dashed line is the view from Earth. The outer drawings give the appearance of the rings as seen from Earth. (Reprinted with the permission of Cambridge University Press.)

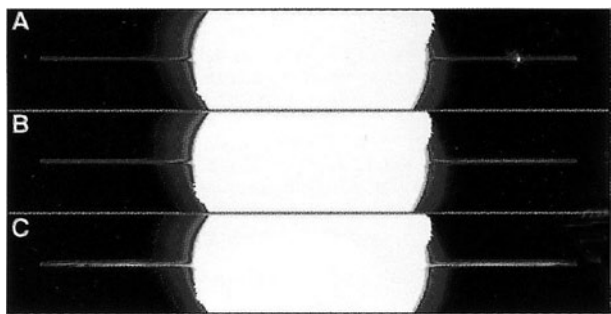


Figure 2.4 A sequence of Hubble images at $0.89\,\mu\text{m}$ obtained on August 10, 1995 as the Earth crossed Saturn's ring plane, at (A) 20:12, (B) 21:49, and (C) 23:42 UT. Each frame is a composite of two images, processed to remove cosmic rays and small satellites. Dione is visible 17 arcsec west of Saturn in (A). The planet's disk is heavily saturated in these 300-s exposures. North is at the top, 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.)

universe (van Helden, 1984). At the Creation, God had put all extended substance in the universe in motion in vortices. Our solar system was but one. Planets moved in the solar vortex and were themselves centers of smaller vortices. For example, Jupiter's vortex accounted for the motions of the Galilean satellites (Descartes, 1644, 80–202). Huygens thought in terms of *Cartesian* vortices. When he discovered Saturn's satellite Titan in 1655, he knew that Saturn's vortex extended that far, including the rings.

Since Huygens determined Titan's period to be 16 days, he believed that the rings' material must revolve faster, but not as fast as Saturn itself (which he concluded rotated in 1/2 day by analogy with the Earth and its moon). Since he saw no variations on this scale of days (the puzzling behavior that was observed extended over Saturn's orbital period of 29 years), he naturally thought in terms of a symmetric ring, flat and not varying, around its circumference. Only a body symmetrical around the axis of rotation of Saturn's vortex could solve this problem (van Helden, 1984). Thus, it is clear that Huygens was drawn to the correct solution as much (or more) by his philosophical conceptions as by his own observations. 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 revise 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 us to drop the simple models and embrace a much more complicated and active view of planetary rings. The rings have continued to change between the Voyager and Cassini missions. Richard Greenberg and Andre 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.

The interplay between observations and theory is clearly seen in the history of ring studies. From the first, the quality of the observations fell just short of revealing the rings' essential nature. Galileo's observations allowed multiple explanations. Huygens' revelation was the result of new thinking and application of the Cartesian world-view, rather than better observation. Similarly, Huygens imagined the ring around Saturn as a solid body. The discovery of a gap in Saturn's ring by Jean Dominique Cassini in 1676 (now known as the Cassini Division) led many to the idea that the rings were composed of multiple satellites. Nonetheless, Huygens never abandoned his original proposal of a solid, thin ring.

Saturn's ring served as a model for the overall structure of the universe in the cosmology of the seventeenth through nineteenth centuries. The philosopher Immanuel Kant applied this disk model to the "nebulae," or clouds, seen in the telescope, which we now know to be galaxies of countless stars. Kant proposed that God had brought about the current situation by using natural forces. Matter became concentrated in rotating nebulae and was flattened as a result of this rotation into individual galaxies, stars, and planets. This nebular hypothesis is still the paradigm for planet formation; and the rotation is presently seen as the explanation for the flatness of planetary rings. Thus, since the middle of the eighteenth century, the flat disk (of which Saturn's ring was the local example) has become an ever-present cosmic model.