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The Ringed Planet

Cassini's voyage of discovery at Saturn

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In memory of my father. Always an inspiration.

Contents

Preface

One of the wonderful things about the Saturn system is that there is so much happening in it that it can almost be used as a review of planetary sciences in general. And that is also the challenge in writing a book about the system. Like the Cassini mission itself, this book explores Saturn, its rings, moons and magnetosphere. That's a lot of material to cover in a limited space. I emphasize the physical processes that have shaped the Saturn system, using some of the most dramatic and intriguing discoveries made by Cassini at Saturn as case studies to illustrate these processes. The book is written for a general audience, and it is also appropriate as an introduction to planetary sciences for students.

Cassini's observations of Saturn, spanning more than 13 years, have revolutionized our understanding of the planet, its complex ring system, and many of its moons, especially Enceladus and Titan. I have always been interested in why things are the way they are, and there are many astounding observations made by Cassini that demand an answer to the question 'why is that?'. We have answers to that question for many of Cassini's discoveries, and this book covers a diverse set, from the origins of dusty ring particles to the heart of the giant planet itself. I emphasize links between the phenomena at Saturn and planetary systems in general. And still this only scratches the surface. There are many more intriguing phenomena and discoveries that I could not include without having the book expand to several times its current length. I hope the reader is inspired to learn more about this fascinating planet and its family of rings and moons. The images in this book are also just a sampling of those returned by Cassini to illustrate the physics described in the book and to whet the appetite of the reader to discover more at the public repositories of all Cassini data.

Acknowledgments

I am one of the lucky few who has worked on the Cassini mission continuously for more than a quarter century, and I owe that opportunity to Larry Esposito, my dissertation advisor and Principal Investigator of the Cassini Ultraviolet Imaging Spectrograph. I thank my colleagues on the Cassini UVIS team and the project in general for making the mission not only a scientific success but a wonderful working environment all these years. I thank all those scientists whose work has provided the substance for this book. Several more books could be filled with stories of discoveries that space did not permit me to include here.

Thanks to Mark Lewis for his amazing simulation of the rings, Joe Spitale for providing a mosaic of the A ring edge, and Richard Jerousek for his figure of self-gravity wakes in stellar occultation data. I received invaluable early feedback from my mother, Ann Colwell, who let me see the material through the eyes of a non-scientist. I could not have written this without the unwavering support and encouragement of my wife, Anne-Marie.

About the author

Joshua Colwell

Dr Joshua Colwell is a Planetary Scientist and Professor of Physics at the University of Central Florida with a PhD in Astrophysical, Planetary and Atmospheric Sciences from the University of Colorado. His research interests are in the origin and evolution of the solar system with a particular emphasis on planet formation, planetary rings and interplanetary dust. He is a Co-Investigator on the Ultraviolet Imaging Spectrograph on the Cassini mission. He studies the structure and dynamics of Saturn's rings with data from Cassini. He is the Director of the Center for Microgravity Research at UCF. His experiments have flown on the Space Shuttle, the International Space Station, suborbital rockets, parabolic airplane flights, and he is developing a CubeSat for launch in 2017. An avid Trekkie, his other interests include running, writing and movies. He produces and hosts the astronomy podcast 'Walkabout the Galaxy'.

Chapter 1

Introduction

Saturn is not the largest planet in the solar system, but its spectacular ring system sets it apart. The diversity of its moons and the interactions among the moons, and between the moons and rings and Saturn itself, provide case studies in virtually every aspect of planetary sciences, including geophysics, fluid physics, celestial dynamics, plasma physics and cosmochemistry. The international Cassini mission to Saturn had as its goal to study all the phenomena and bodies in the Saturn system, and this book is possible due to the vast amount of data collected by Cassini and the work done by thousands of scientists to analyze and interpret its findings.

I began working on the Cassini mission as a post-doctoral researcher at the University of Colorado in 1990 for my PhD advisor Professor Larry Esposito who had just been selected to provide the Ultraviolet Imaging Spectrograph (UVIS) for the mission. At that point, Cassini existed only as a design, and that design evolved significantly before it was built and eventually launched on October 15, 1997. My graduate research had focused on the ring systems of Uranus and Neptune using data from the Voyager 2 spacecraft, and now I had the opportunity to be involved in a NASA flagship mission to the most stunning ring system known.

Cassini (figure 1.1) arrived at Saturn on July 1, 2004, and since that time we have had the privilege to explore strange new worlds, moons with oceans hidden in their interiors that might harbor life, a dynamic ring system with moonlets forming and fragmenting before our eyes, and at the center of it all a planet with swirling storms that still guards many secrets about its origin and evolution.

The six-and-a-half years of Cassini's flight through interplanetary space to Saturn were anything but dull for those of us working on the mission. The original 'nominal' mission for Cassini had a duration of four years, and every scientist and science group wanted to ensure that those four years provided the best measurements of each aspect of the Saturn system. The project was organized into science 'discipline working groups' focusing on the five aspects of the Saturn system that Cassini was to explore: the planet, Saturn's large moon Titan, the rings, the

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Figure 1.1. The Cassini spacecraft, nearly in flight configuration. The radioactive isotope thermoelectric generators (RTGs) have not yet been installed. The gold wrapping is thermal insulation to help the spacecraft regulate the temperature of its computers and instruments. Image Credit: NASA/JPL.

magnetosphere, and the remaining icy moons. Each group had representation from each of the 12 instruments on Cassini, and the Titan group also included the Huygens Probe team managed by the European Space Agency (ESA). In a model of international scientific cooperation, Cassini transported the ESA-built Huygens probe to the Saturn system where it was deployed for a dramatic descent through Titan's atmosphere and a soft landing on its surface.

In order for the mission to succeed, the spacecraft would have to perform observations of dozens of moons, explore a magnetosphere filling a volume of space larger than the Sun, study a ring system that nearly vanishes when viewed edge-on, map the surface of a moon completely shrouded by haze, and study the atmosphere of the second-largest planet in the solar system without the pesky rings getting in the way. Mission designers at NASA's Jet Propulsion Laboratory spent years developing a variety of 'tours' for Cassini to follow during its four-year mission. These tours were designed to try to meet the demands of each discipline working group each of which, itself, had long and sometimes incompatible demands from their various instrument representatives. The first tour design I worked with as a member of the

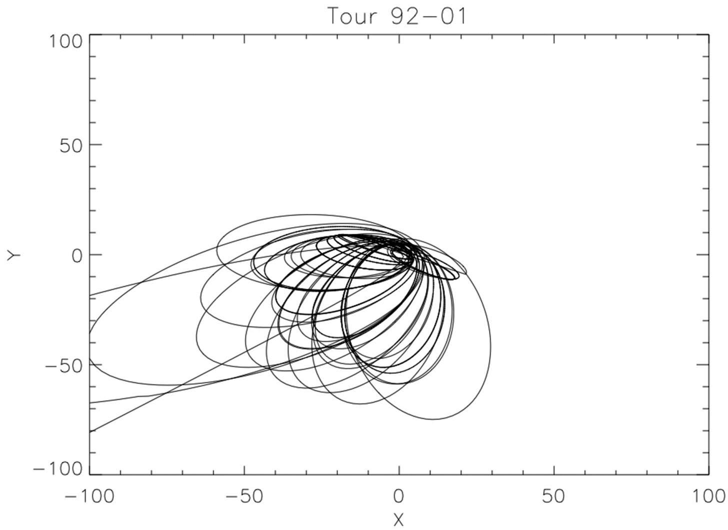

Figure 1.2. The figure shows the path of Cassini in 'tour' 92-01 as seen from above Saturn's north pole. The units on the *x*- and *y*-axes are in Saturn radii.

Rings Discipline Working Group (RWG) was named 92-01: it was the first tour designed and distributed to scientists in 1992 (figure 1.2). Cassini scientists spent many hours drafting strawman timelines for observations using 92-01 and assuming a design of the Cassini spacecraft that was itself soon to change. Originally planned to have a large 'scan platform' that would hold most of the scientific instruments on an arm that could point at anything while the spacecraft antenna points at Earth, Cassini was forced by budget cuts to a redesign in which all instruments are firmly bolted to the body of the spacecraft. This descope of the mission meant that the entire spacecraft would have to act as the scan platform, and that remote-sensing observations with cameras could not be carried out simultaneously with data transmissions to Earth[1]. This made the planning of Cassini's observation timeline that much more difficult. Not only was the amount of time available for scientific observations reduced by about one third to enable 8–9 h data downlinks each day, but suddenly the amount of time it would take to rotate the massive spacecraft from pointing at one observation target to the next became a critical factor in timeline planning. My early responsibilities for UVIS, and later for the project overall, involved developing software that would be used to help design and plan observations by providing visualizations of the Saturn system from the point of view of Cassini. This software was useful in evaluating the observation possibilities provided by a tour.

Years of tour design ensued, with mission designers discovering ever-more inventive and clever ways of using gravitational assists from Titan to enable

[1] A sister mission, the Comet Rendezvous Asteroid Flyby (CRAF) was canceled altogether due to the same budget restrictions.

Cassini to explore as much of the Saturn system as possible in just four years. Cassini spends almost all of its time falling around Saturn, just as the International Space Station falls around the Earth every 90 min. The length of time to complete an orbit is determined by the size and shape of the orbit and the mass of the planet. Designing a tour that flies by the most distant moons, spends time in the equatorial plane to provide unobstructed views of Saturn, flies by Titan at different geometries to allow cloud-penetrating radar to map most of the surface, and flies high over the poles of Saturn to allow views of the rings is a highly over-constrained problem. It takes time to get to all of those places and vantage points, and many of the targets are moving. Complicating matters, certain instruments had key observations that required special orbits to allow observations of the Sun or the Earth as they passed by the atmospheres of Saturn and Titan and by the rings that needed to be made at a certain seasonal date in Saturn's year. All of this needed to be done using essentially no fuel, instead using gravitational encounters with moons to slingshot the spacecraft from one orbit to the next.

Each discipline working group produced spreadsheets filled with green, yellow and red cells indicating how well each candidate tour fared in meeting science goals. The tour ultimately decided upon was nicknamed T18-5TDJ4 (figure 1.3), for the fifth variant of the 18th Titan-class Tour[2]. A visual comparison of the paths for Cassini in 92-01 (figure 1.2) and T18-5 (figure 1.3) makes it immediately clear that the later tour, using clever tricks of celestial mechanics, was able to explore much more of the Saturn system.

Once the tour was decided upon, years of observation design and sequencing could begin. The tour was segmented into chunks a few days long, and these segments were assigned to groups based on the primary observing target for that period of time. The time near a Titan flyby was assigned to the Titan Orbiter[3] Science Team (TOST). Other groups were identified as 'Target Working Teams' (TWTs) and referred to, believe it or not, as the 'twits'. I was assigned by Larry Esposito to be the representative of the UVIS instrument on the 'rings twit'. We met weekly for several years and later biweekly, almost exclusively by teleconference, to decide what observations would take place during each minute of the time assigned to a rings segment. An example of the observation sequence for a single flyby of the moon Enceladus from SOST (Satellites Orbiter Science Team) is shown in figure 1.4. As I write this, the Rings Twit is finishing the designs on the last rings segment of the Cassini mission: the spacecraft is scheduled to plunge into Saturn's atmosphere on September 15, 2017, bringing to a conclusion one of the most successful and

[2] The TDJ4 addendum stands for 'tour du jour number 4' indicating that this is the 4th version of T18-5. Variations on the main tour were small and designated by various 'tweaks'.

[3] Orbiter here refers to Cassini, and the term is used to distinguish it from the Huygens lander teams. In addition to TOST and the Rings TWT (written this way, but *always* referred to as the 'rings twit'), the project had the Satellites Orbiter Science Team (SOST), the 'mag twit', studying the magnetosphere (Mag TWT), the Atmospheres TWT, and the XD TWT, or 'cross-discipline twit'. It handled time periods when Cassini was far from any object and multiple targets-of-opportunity presented themselves, cutting across scientific disciplines. My friend and colleague at JPL, Kelly Perry, who steered the XD TWT with a famously strong hand at the helm, was dubbed 'the dominatrix of cross discipline'.

(a)

(b)

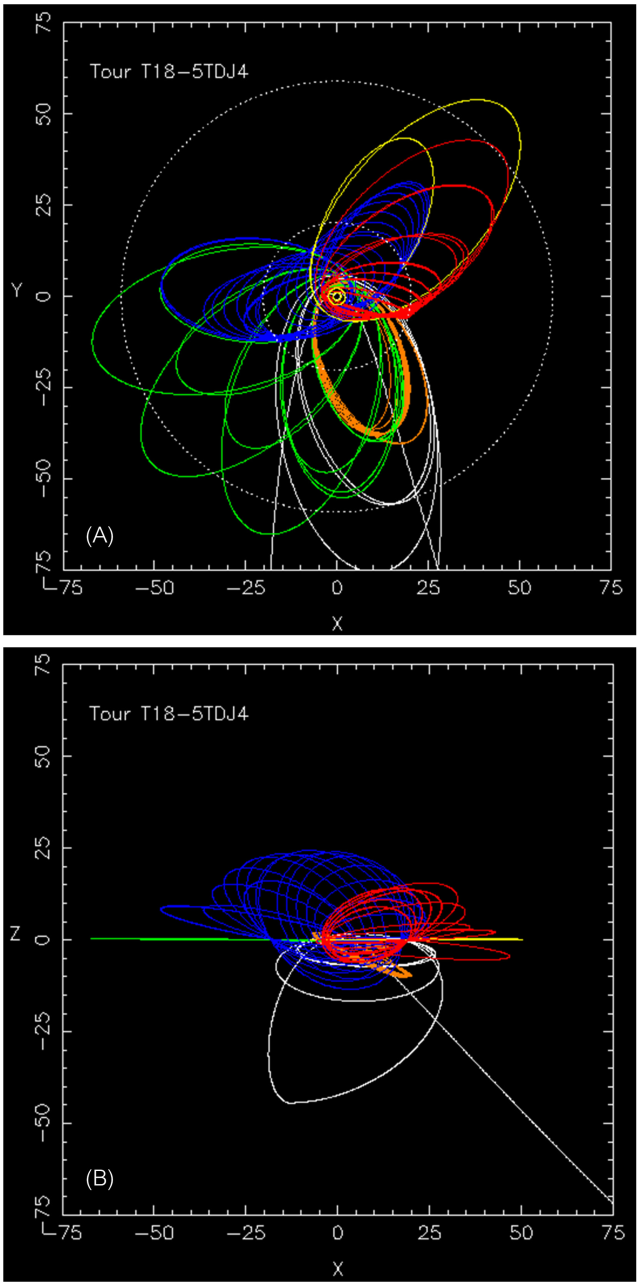

Figure 1.3. (a) The colored lines show the path of Cassini for four years viewed from above Saturn's north pole in the selected tour T18-5TDJ4. The colors indicate different phases of the mission. The two yellow circles at the center are Saturn and the outer edge of the rings. The white dashed lines are the orbits of Titan (inner) and Iapetus (outer). The initial orbits are in white, and the final orbits in red. (b) The T18-5TDJ4 tour seen from Saturn's equatorial plane. Cassini arrived from the South due to the season at Saturn (white curves). The green orbits were in the equatorial plane and appear as a line here, seen edge-on.

Figure 1.4. Illustration of the observation plan for the flyby of Enceladus on Cassini's 61st orbit of Saturn. The different panels show the maneuvers of Cassini and the views of the different instruments responsible for observations during those times. Movie Credit: NASA/JPL.

ambitious planetary missions in history and one that has spanned my entire professional career.

A book about the Saturn system as a whole could easily fill several volumes. Indeed, the number of refereed scientific papers published based on results from the Cassini–Huygens mission is over 3700 as of December 2016. Discoveries will continue to be made with the wealth of data returned from Cassini for many years after the spacecraft is no longer with us. The Saturn system is dynamic in many ways: the rings, moons, and planet have changed before our eyes during the dozen years of exploration by Cassini. While the book is loosely organized by object or class of object (moons, rings, planet), this is a book about *why* things are the way they are, rather than just *what* things look like. Such is the scale and diversity of the Saturn system that virtually every important physical process in planetary science is at work or has left its mark somewhere in it. Each object in the Saturn system illustrates the laws of physics at work in unusual environments with sometimes surprising consequences. While this is a book about the Saturn system, it is also a primer on many processes in planetary sciences. We are learning not just about Saturn and its family, but about the history of our solar system as well as the processes that shape planetary systems around other stars.

Chapter 2

Seeing Saturn

Seeing Saturn through even a small telescope for the first time can be startling: a mundane point of light in the night sky, brighter than most stars but otherwise unexceptional, suddenly becomes an alien world with a broad, bright ring around it. Galileo Galilei was the first person to have this experience, in 1610. It is difficult to imagine what this must have been like for him. At that point in time, the heavens were considered known and essentially immutable. Thus the appearance of objects such as comets, temporary interlopers in the night sky (and occasionally even visible in daylight), were thought to portent all manner of evil things. Galileo's observations of spots on the Sun and points of light dancing around the planet Jupiter, itself with noticeable markings, marked the end of ancient astronomy, which was one and the same as astrology, and the beginning of a new era of scientific observations of the sky. From that point forward, objects in the sky could be studied in detail, new objects discovered, and the nature of the wandering points of light could begin to be explained.

Over the next two years of observations through his low-grade telescopes, among the first to be pointed at any celestial object, Galileo saw Saturn's large moon-like extensions that resembled giant ears on the planet more than anything else, gradually shrink until they disappeared. This was not only further evidence of the changing nature of objects in the sky, but was both unprecedented and difficult to understand. Galileo originally thought that Saturn was a triple-planet, then to his amazement saw the two smaller orbs shrink and disappear. Before he could question his sanity the extensions eventually reappeared. With the improvement of telescopes, the Dutch astronomer and physicist Christiaan Huygens deduced the geometric nature of Saturn's odd shape in 1656. It was common at the time for scientists to publish anagrams that encoded their discoveries prior to releasing a book containing a full explanation. Huygens announced in an anagram (in Latin) that Saturn's odd appearance could be explained by a thin flat ring circling the planet but not in contact with it. The changing appearance (by this time the ring had disappeared four

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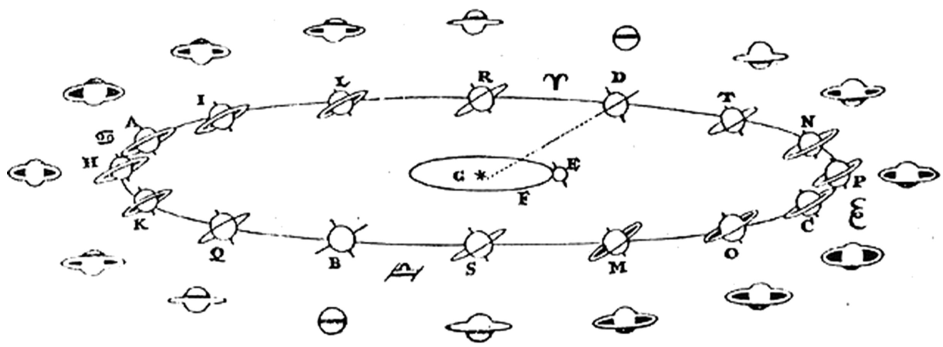

Figure 2.1. Christiaan Huygens' geometric model of Saturn's rings, the first to correctly explain the odd appearance of Saturn through the telescopes of the first half of the 17th century. The Sun is marked by the asterisk at the center, and the orbits of the Earth (E) and Saturn are shown. With Saturn's rotation axis tilted (not pointing straight up, in this picture), the rings appear edge-on from the point of view of the Earth twice each Saturn orbit (at points B and D), and they present their maximum opening at points A and C. The Earth's axis is also tilted with respect to its orbit, and this is why we have seasons: in the summer the Sun is more directly overhead, while six months later the opposite hemisphere is more directly illuminated. From Huygens' *Systema Saturnium*, 1659.

times at 15 year intervals) was due to a tilt of the axis of the ring with respect to Saturn's orbit around the Sun (figure 2.1).

Kepler, at about the same time that Galileo was making his revolutionary observations, had provided a robust and simple mathematical model for the motion of the planets around the Sun that essentially confirmed the heliocentric picture of the solar system first put forward by Nicolas Copernicus. Kepler's model explained that Saturn's 29.5 year orbital period was a consequence of its great distance from the Sun, on average 9.55 AU[1]. Huygens recognized that if Saturn's rotation axis were tilted with respect to the plane of its orbit around the Sun, similar to the tilt of the Earth's axis that gives rise to our seasons, the rings would at times appear to us edge-on, and at other times closer to face-on. Thus, the rings disappear from our vantage point on the Earth twice each Saturn orbit, at the Saturnian equinoxes (the equivalent of our starts to the spring and fall seasons) when they appear to us edge-on (figure 2.1). In between, at Saturn's Northern and Southern solstices (the equivalent of the starts of the summer and winter seasons on Earth), Saturn's rings are at their most open aspect to the Earth. Because Saturn's rotation axis, which is also the axis of the rings, is tilted 26.7° with respect to its orbit, we are able to see the rings more, or less, open over the course of a Saturn year.

The progress in telescope technology since the 17th century led to the discovery of structure within the ring and several moons. Huygens discovered Saturn's largest moon, Titan, in 1655, and four smaller moons, Tethys, Dione, Rhea and Iapetus were discovered shortly thereafter by Giovanni Domenico Cassini. Cassini also discovered a major gap in the ring system now known as the Cassini Division, and it is for him that the international Cassini mission to Saturn, whose observations have

[1] 1 AU = 149 000 000 km is the mean distance of the Earth from the Sun.

rewritten our understanding of Saturn and its place in the solar system, is named. Mimas and Enceladus were discovered by William Herschel in 1789, and two smaller moons were discovered in the 19th century. Mimas and Enceladus are next door neighbors at Saturn, and comparable in size, but the similarities end there. Mimas is just what we would expect of a small icy moon, its surface literally saturated with craters, with one crater so large that its formation came just shy of destroying Mimas entirely. Enceladus, only slightly larger, on the other hand, is one of only a handful of geologically active objects in the solar system. It spews water vapor out of a system of vents near its south pole, resulting in the ephemeral E ring of Saturn.

It was not until 1966 that a 10th satellite of Saturn, Janus, was discovered by taking advantage of the reduced light from the rings during a Saturn equinox (a ring-plane crossing like that shown in figure 2.1 at points B and D). The first spacecraft to visit Saturn were the Pioneer 11 and Voyager 1 and 2 explorers of the outer solar system in 1979, 1980, and 1981, respectively. These visits led to the discovery of details in the rings down to the resolution limit of the cameras and several more small moons. While the rings had previously been assumed to be essentially featureless and uniform disks of material leftover from the era of planet formation, the Voyager images showed the rings to be full of unexplained structure. By the time Cassini arrived at Saturn in 2004, 31 moons had been discovered, most of them of the pipsqueak variety less than 50 km in diameter. Dedicated observing campaigns from Earth together with Cassini's cameras have doubled that count, with all of the new moons falling in the tiny moonlet category. Indeed, as we will see, many of the objects discovered by Cassini blur the line between moon and ring particle.

Other advances in observational astronomy led to the discovery of rings around Uranus, in the 1970s, and around Neptune in the 1980s. Jupiter's ring was discovered in images taken by the Voyager 1 spacecraft in 1979. The ring systems of these other planets, while fascinating in their own right, literally pale in comparison to the broad expanse of Saturn's rings (figures 2.2–2.5). As we will see in chapter 5, however, determining just how much material there is in a planetary ring is not straightforward, and knowing the mass of the rings, not just their surface area, is a critical piece of information to understanding their origin and evolution.

While Saturn's rings outshine those of its nearest planetary neighbor, the Saturnian system of moons is oddly deficient compared to Jupiter. The four Galilean satellites of Jupiter, Io, Europa, Ganymede and Callisto, comprise an orderly set of worlds that make the Jupiter system look like a miniature solar system. Io, the innermost of Jupiter's moons, is the densest, while the most distant, Callisto, is the iciest and least dense, a trend in composition that mirrors the trend seen in the inner planets of the solar system. Mercury, the innermost planet, is iron rich, while the Earth has a modest complement of water and other volatile materials that are in the vapor phase at the high temperatures close to the Sun. When Jupiter and Saturn formed, temperatures in their neonatal system of moons and rings would also have been higher close to the central body, a planet in this case, rather than the Sun, so it is not surprising to see ice-poor Io close to Jupiter and ice-rich Callisto further away. Saturn, unlike Jupiter, has a single giant moon, Titan, second only to Ganymede in size, and the largest in the solar system if one measures to its

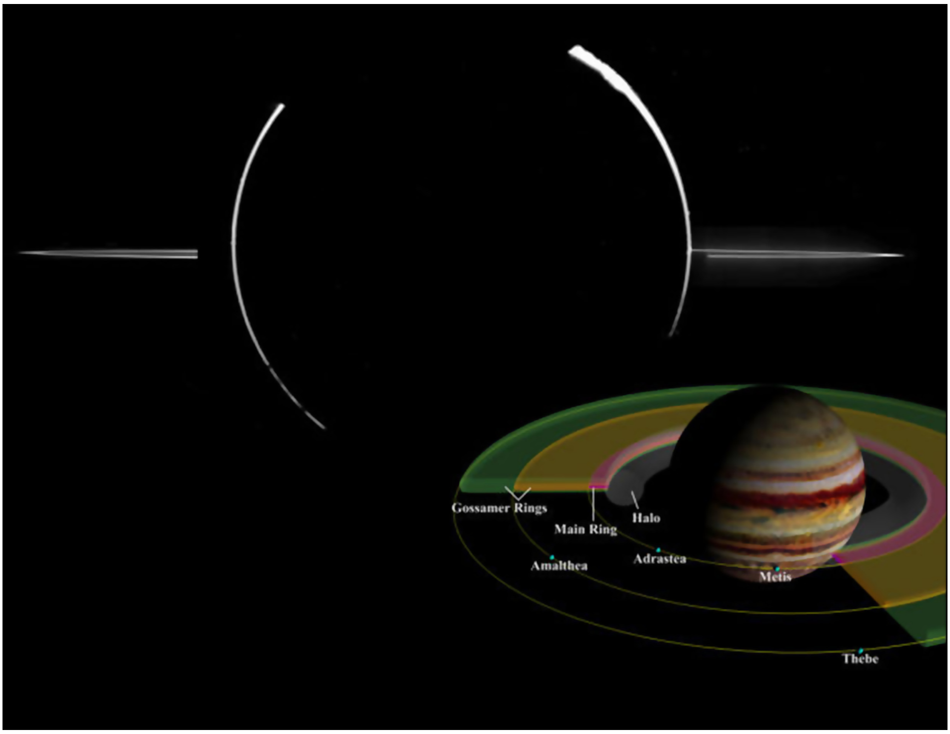

Figure 2.2. The Jovian ring, seen in forward-scattered sunlight in a mosaic of images taken by the Galileo spacecraft on November 9, 1996, at a distance of 2.3 million km, when it was in orbit around Jupiter. The Sun is behind the disk of Jupiter, so only light shining through the upper atmosphere of the planet can be seen, as well as the dusty rings which are best-observed in this geometry due to the small size of the particles (~1 μm) and the tenuous nature of the rings. From our vantage on the Earth, the rings are so transparent as to render them virtually invisible. A schematic of the rings and nearby moons is shown in the lower right. Image Credit: NASA/JPL/University of Arizona.

cloudtops instead of the solid surface. Aside from Titan the remaining moons of Saturn are middling in size, at best. The differences between the two satellite systems may be related to the ultimate reason for the existence of Saturn's rings. One thing is certain, however, and that is that neither Jupiter nor Saturn formed in isolation. The individual peculiarities of each system are clues to the formation of the planets, reshuffled through billions of years of dynamical and geochemical evolution, but detailed and distinct enough to place strong constraints on the story of the formation of our solar system.

The Cassini spacecraft, which arrived at Saturn in the summer of 2004, has been collecting evidence from this scene of planetary origins through nearly half of a Saturn year. When it was launched Cassini was the largest spacecraft ever sent to the outer solar system. It was designed to explore all aspects of the Saturn system, including the rings, moons, and magnetosphere as well as the planet itself. Cassini carried with it the Huygens probe, led by the European Space Agency, to descend through the atmosphere of Saturn's largest moon, Titan. To carry out this

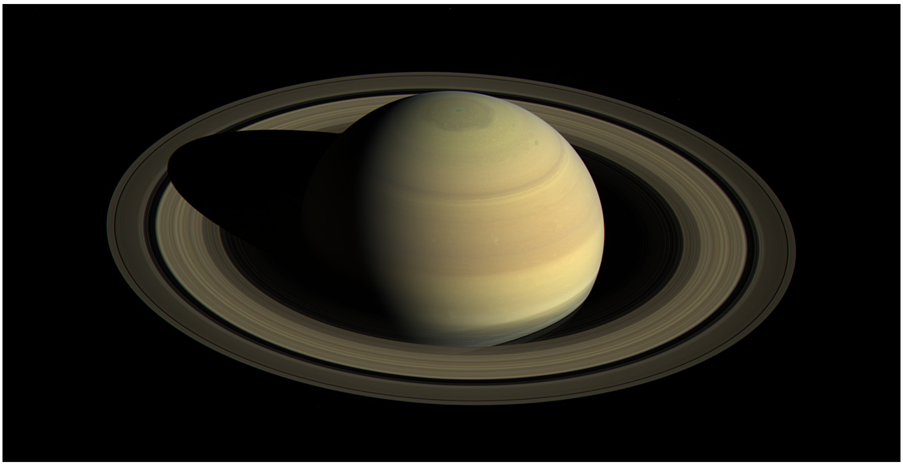

Figure 2.3. Saturn and its rings from Cassini, on April 25, 2016, from a distance of 3 million km and an elevation of 30° north of the ring plane. Saturn's north pole is marked by a hexagonal feature in the clouds. The dark, apparently empty gap outside the bright B ring is the Cassini Division, and is in fact far from empty: it alone has more ring material than any of the other planets. The rings cast a shadow on the planet near the 5 o'clock position, and Saturn returns the favor, casting its own shadow on the rings that varies over the course of its 29.5 year journey around the Sun. Image Credit: NASA/JPL/SSI.

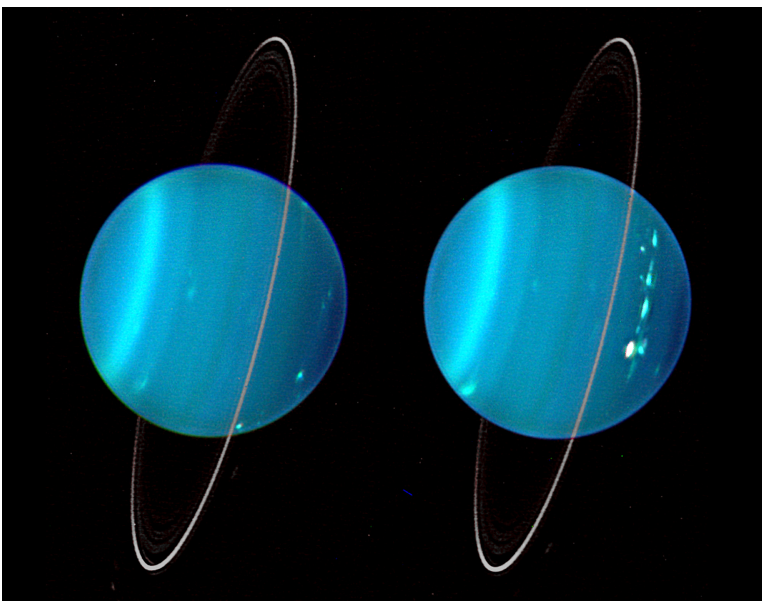

Figure 2.4. The rings of Uranus were detected from Earth-based observations of a stellar occultation in 1977, in which the brightness of a star is measured as it passes behind another object. Nine narrow rings were detected this way as narrow dips in the star brightness on either side of Uranus, before Voyager 2 encountered Uranus in January 1986 providing the first images. Here the rings are seen in infrared images taken at the Keck telescope in July 2004 using adaptive optics. The outermost ε ring is most prominent, and is only about 50 km in width. Image Credit: Lawrence Sromovsky, University of Wisconsin-Madison, W M Keck Observatory.

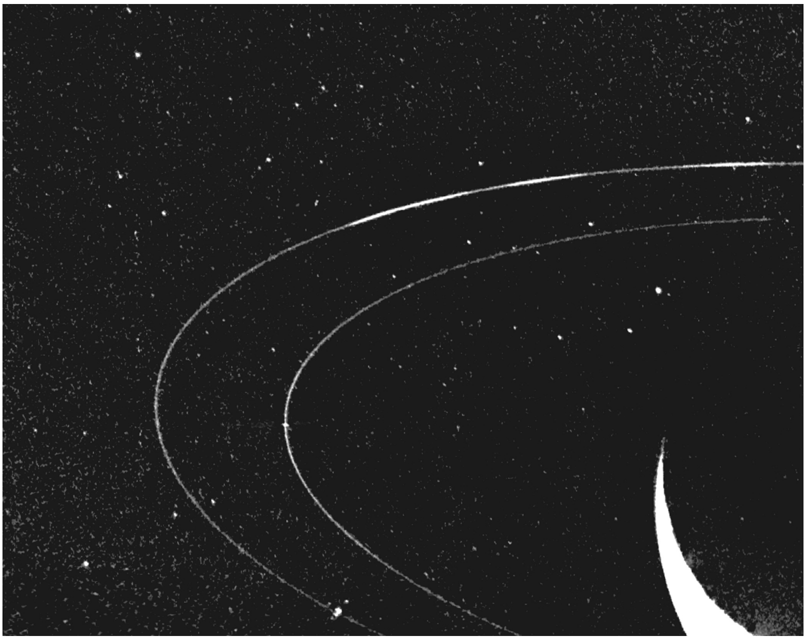

Figure 2.5. Voyager 2 acquired this image as it encountered Neptune in August of 1989 looking back toward the Sun to accentuate the appearance of the narrow dusty rings, similar to the viewing geometry of figure 2.2. The overexposed limb of Neptune is visible at lower right. In Neptune's outermost ring, material mysteriously clumps into three arcs (top). Earth-based images taken since the Voyager 2 flyby show that the arcs have evolved and rearranged their orientation. Image credit: NASA/JPL/University of Arizona.

exploration, Cassini was equipped with a dozen scientific instruments to see Saturn and its environs from extreme ultraviolet wavelengths through radio wavelengths, while Huygens carried another half dozen instruments to the surface of Titan (figure 2.6). Cassini's four optical remote sensing cameras can see the ultraviolet glow of Saturn's aurora and the feeble thermal emission from 'warm' spots on Enceladus that are nearly 200 °C below zero. The main imaging system has captured stunning views of alien vistas at unprecedented detail, revealing the knobby south-polar terrain of Enceladus and mile-high snowpiles at the edge of the B ring. Its radar can see through the clouds and haze of Titan's thick atmosphere to catch the glint off the surface of its methane lakes. It has detectors to measure the charged particles, atoms, and dust particles as it flies through the system, hear the radio emission from lightning on Saturn, and literally sniff the plumes of Enceladus and taste the dust of the E ring. Originally planned for a four year mission at Saturn, the wealth of information returned by Cassini and the excellent performance of the spacecraft and its scientific instruments enabled it to continue exploring the ringed planet for nearly two full Saturn seasons. Even its planned demise on September 15, 2017, exactly one month shy of its 20th anniversary in space, will yield critical information about Saturn, its interior, and its rings.

The Cassini mission has been an inspiring story of international scientific collaboration with participation from 17 countries to answer some of the fundamental

Figure 2.6. The Cassini spacecraft is the largest interplanetary probe to date, measuring 6.8 m in length. The large cone-shaped object on the right is the protective atmospheric aeroshell for the European-managed Huygens probe. The 4 m dish antenna is both a communications device and a scientific instrument in its own right. Some of the optical cameras are visible at left. Image Credit: NASA/JPL.

questions about our solar system. Amazingly, rings that were once thought to be static ruins left over from Saturn's formation 4.5 billion years ago have changed before our eyes. Moons swap orbits and launch waves that march across the rings, while elsewhere moons form and break apart within the rings themselves. Cassini has discovered new moonlets that may be nothing more than sandpiles in space, and geysers erupting from Enceladus, a moon roughly the size of the state of Colorado. Lakes and clouds on Titan come and go with the seasons, but are composed of methane rather than water. Storms flare up in the planet's atmosphere, and ripples in the rings hint at massive invisible storms or other anomalies deep within the planet. Even the rotation of the planet itself seems to change, an illusion caused by variations in its magnetic field. This dynamic system, still evolving after billions of years, is a keystone in the architecture of our solar system, and its story, dramatically, but only partially, unveiled by observations from Cassini, illuminates our own history as well as the formation of planets throughout the Galaxy.

Further reading

Following the conclusion of Cassini's initial four year mission at Saturn two volumes of review articles on the Saturn system and on Titan were produced (Dougherty *et al* 2009, Brown *et al* 2009). These are comprehensive technical overviews of the system as of 2009. Detailed reviews of the instruments on the Cassini orbiter and the Huygens Titan probe were published in the journal *Space Science Reviews* and collected in three volumes in 2003–2004 (Russell 2003, 2004a, 2004b).

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Chapter 3

Why are there moons and rings?

In order to understand the origin of Saturn's moons and rings we must first explore why rings continue to exist at all. If we could get close enough to Saturn's rings we would be able to identify individual ring particles. We believe these would look something like snowballs, ranging in size from a few millimeters to a few meters. In some locations these particles would be clustered together, forming aggregates that could stretch for more than 100 m in length. For the moment, though, such an observation remains tantalizingly just beyond our grasp. Larger clumps, whose origins are not as well understood, have been seen by Cassini and are discussed in chapter 5. Nevertheless, we have learned a lot about the sizes and compositions of these particles from their collective behavior. Each ring particle is, in a sense, a moonlet of Saturn. A ring particle orbits Saturn just as a moon does, with two important distinctions: they are typically much smaller (less than 10 m) than anything we would identify as a moon, and they are orbiting within a crowd of other ring particles that are frequently jostling against them, sometimes even sticking together for prolonged periods of time. There are, however, objects within the rings that, were they not within the rings, we would likely designate as moons. And there are small moons that, if we placed them within the rings, we might identify as anomalously large ring particles.

In this chapter we will see that the reason for the existence of rings has to do with proximity to Saturn. Rings exist close to the planet, and further away we find individual moons. There is a transition region from rings to moons where both co-exist. The gravitational pull between the ring particles tries to make them accrete into moons, but close to Saturn the effects of Saturn's gravity inhibit this accretion. We begin with a brief survey of the many objects orbiting Saturn, some within the rings, some quite distant, and some themselves the sources of faint rings.

Taking a census of these objects, there are 53 objects orbiting Saturn that have been given names as moons of Saturn, from Aegaeon, a scant 250 m in diameter, which orbits within (and contributes to) the ghostly G ring (figure 3.1), to Ymir, a small distant moon on a retrograde (backwards) orbit. Nine additional objects

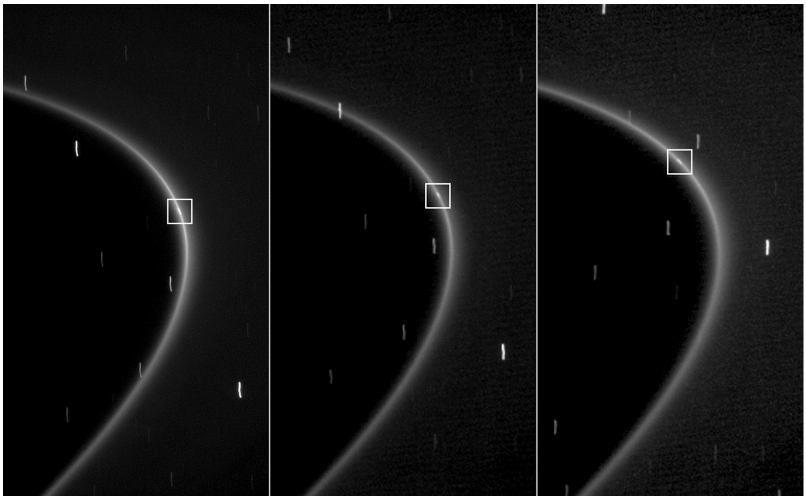

Figure 3.1. These three images taken at 5 min intervals by Cassini on June 11, 2004, show the faint G ring and the tiny moon Aegeon. The background streaks are stars, blurred by the long exposure necessary to capture the faint ring. Micrometeoroid impacts onto Aegeon knock dust off the surface which eventually spreads into the G ring around Saturn. Image Credit: NASA/JPL/SSI.

have not been officially dubbed by the International Astronomical Union, but eight of them, like Ymir, are small objects orbiting far from Saturn on retrograde orbits. The planets and most moons in the solar system travel in the same direction in their orbital motions, and with few exceptions they rotate in that same direction. Viewed from far above the north pole of the Earth, we would see the rotation of the Earth, and the orbital motion of most moons, all planets, and all asteroids to be in the counterclockwise direction. This sense of orbital motion and rotation is called *prograde*. It is a relic of the original motions of all the gas and dust in the cloud that collapsed to form the solar system.

Retrograde moons orbit in the opposite sense (clockwise, as viewed from above Saturn's north pole). This indicates that they were captured by Saturn from interplanetary space and that they were not part of the original disk of material that Saturn and its regular satellites formed from. The ninth provisional moon of Saturn is not on a retrograde orbit, but is an object within the rings themselves (figure 3.2). Due to its location and its small size (less than 200 m out of the plane of the rings), it is unlikely it will be observed from the ground, so confirmation of its continued existence will await some future mission to Saturn.

The captured moons, like the two moons of Mars, Phobos and Deimos, are asteroids or comets that formed elsewhere in the solar system along with all the other small objects that eventually became parts of the planets themselves. Over time, their orbits evolved due primarily to gravitational perturbations from the planets. When an object orbiting the Sun passes close enough to a planet, that planet's gravity can alter the orbit. Even at great distances, gravitational perturbations can build up over time and result in large changes in an object's orbit. The asteroid belt, for instance, is heavily sculpted by the effects of Jupiter's gravity even at a distance of 2–3 AU. If an asteroid or comet comes close enough to a planet, it may become captured into a

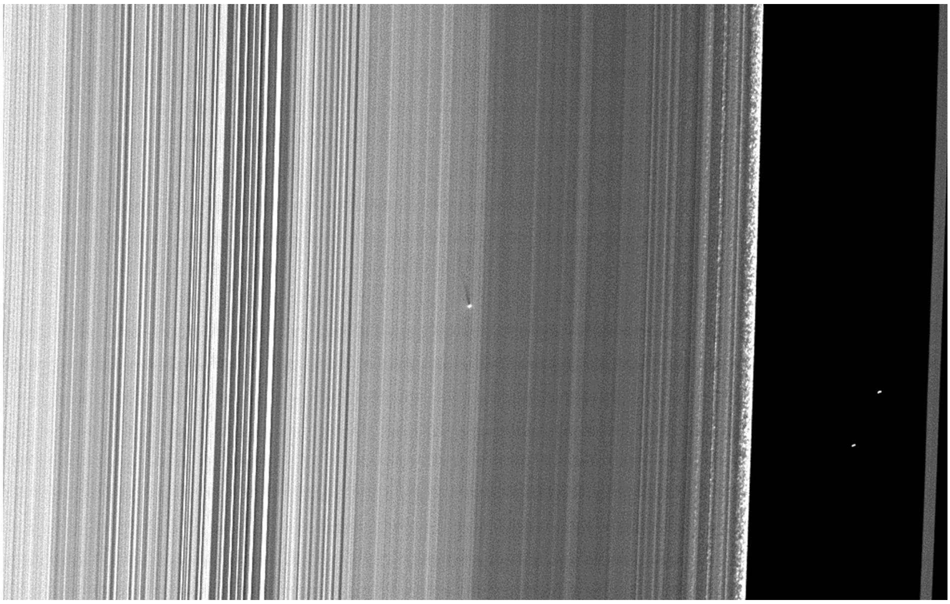

Figure 3.2. Cassini image taken on July 26, 2009, of the outer edge of Saturn's B ring showing an object (bright point near center) casting a shadow on the rings. From the extent of the shadow (36 km) and the position of the Sun, S/2009 S1, as it is provisionally known, is protruding 150 m above the rings (and presumably below it as well), but the width of the shadow indicates it is much wider than it is tall. The mottled appearance at the edge of the ring is due to clumping of ring particles. The two bright spots in the Huygens gap to the right of the ring edge are background stars, and the narrow band at the right edge of the image is the Huygens ringlet. Image Credit: NASA/JPL/SSI.

new orbit around the planet. Frequently, but not always, these objects are on retrograde orbits, and they are almost always on very distant orbits from the planets. Although most of Saturn's captured moons are small (all but one is less than 40 km across), they dominate the planet's moon tally. Fully 38 of Saturn's moons, including eight of the provisional ones, are irregular, captured satellites. Phoebe, at over 200 km in diameter, is by far the largest of the captured moons (figure 3.3).

Although heavily cratered, Phoebe is nearly spherical in shape with dimensions of 219 by 204 km. This is a bit smaller than the maximum size for a non-spherical object. Rocky or icy objects with typical densities will naturally deform into a spherical shape[1] under the influence of their own gravity when they are larger than about 300 km in diameter. Phoebe's nearly spherical shape may thus be partly due to chance, though it may have been somewhat larger (and more spherical) when it first formed. Like most of the irregular satellites, Phoebe is on a retrograde orbit around Saturn. It was likely captured by Saturn's gravity after migrating inward from the Kuiper Belt, the region of the solar system beyond the orbit of Neptune. In addition to the orbit pointing to a capture origin for Phoebe, its surface characteristics are quite distinct from those of the bright inner moons of Saturn which are

[1] More generally bodies deform into an ellipsoidal shape due to the effects of rotation which tend to flatten objects, and tidal forces, discussed below, which tend to stretch them.

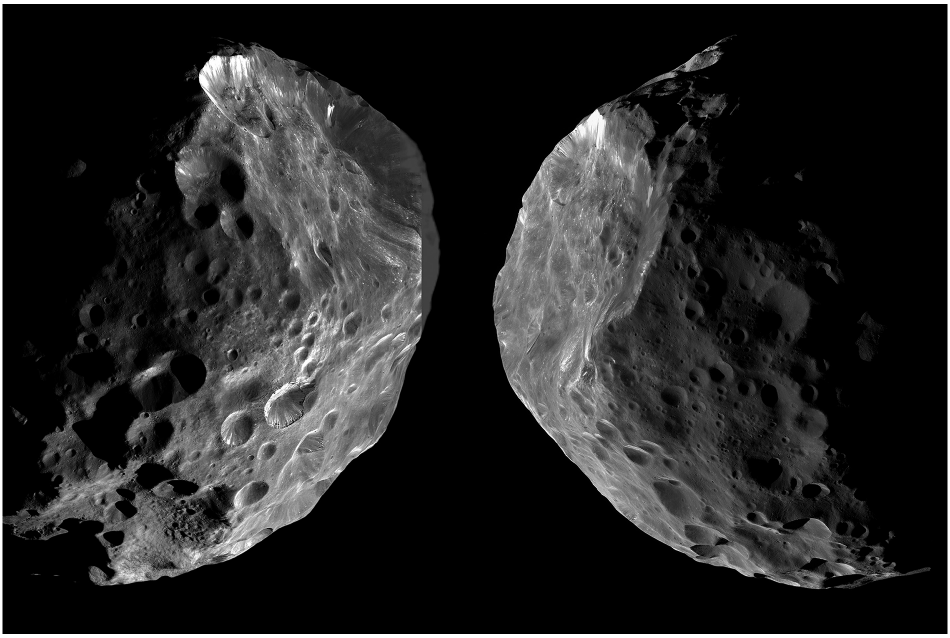

Figure 3.3. Saturn's largest 'irregular' satellite, Phoebe, was visited once by Cassini on June 11, 2004. Left: arrival view. Right: departure view. Image Credit: NASA/JPL/SSI.

predominantly water ice (chapter 4). The reflectivity of the surface is on average only about 6%, a value that we would perceive as black, but some craters reveal ice beneath the dark surface deposits. Cassini measurements show the presence of carbon dioxide ice on the surface of Phoebe which points to an origin in the cold, outer solar system rather than in the asteroid belt, for example. Some of the impacts that formed these large craters, in addition to deforming the shape of the moon, may have knocked chunks of material off Phoebe that we now see as small moons of Saturn on orbits similar to that of Phoebe.

Two other moons have been observed within the rings: Pan, discovered by Mark Showalter in images taken by Voyager 2, and Daphnis, discovered in images taken by Cassini cameras (figure 3.4). Each of these moons creates a gap in the rings, and both gaps are in the outer portion of the main ring system. In spite of extensive imaging campaigns by Cassini to locate moons in other gaps in the ring system, none has been discovered. Since nature abhors a vacuum, gaps in the rings require some explanation. Over time we would expect the ring particles to gradually diffuse into the gap, filling it in. As we will see in chapter 5, the interactions between moons and ring particles have some surprising and counter-intuitive results, one of which is that the moon's gravity effectively repels, rather than attracts, the particles, and in this way moons such as Pan and Daphnis open up and maintain gaps in the rings (figure 3.5).

There are many more objects in the rings that are too small to open full gaps, but leave characteristic propeller-shaped holes in the rings (Sremcevic *et al* 2002). These *propeller objects* may be fragments of larger moonlets, or they may be large collections of ring particles that managed to stick together to form mini-moonlets (figure 3.6).

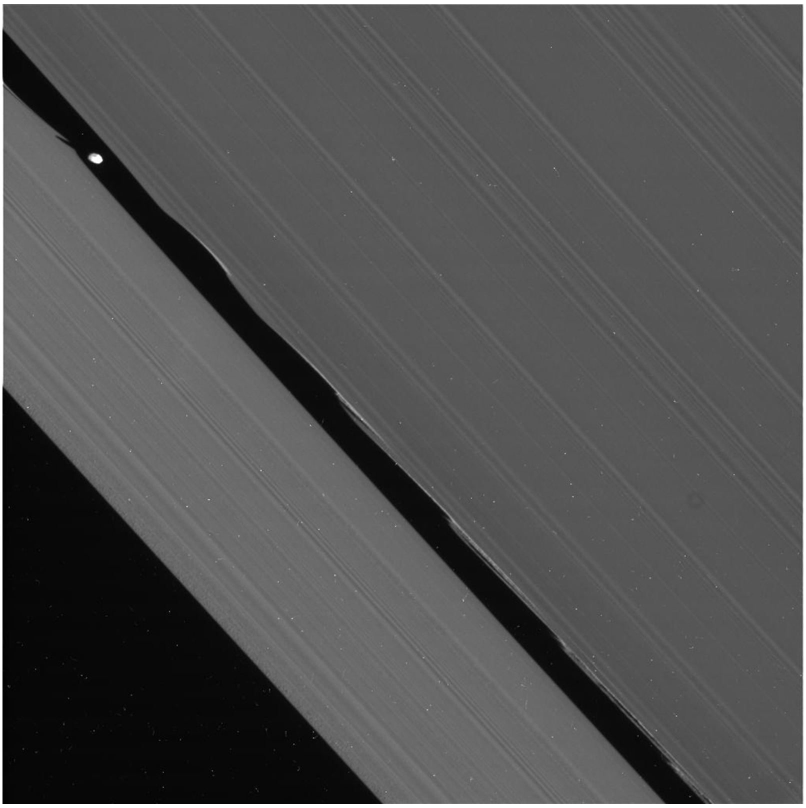

Figure 3.4. The moon Daphnis, upper left, has a mean radius of 3.8 km and is orbiting in the Keeler Gap, just interior to the outer edge of Saturn's A ring (at lower left). The gravitational influence of Daphnis on the ring particles orbiting Saturn on either side of the Keeler Gap results in a wavy pattern. The waves are asymmetrical around Daphnis's position because the particles closer to Saturn (upper right) are orbiting faster than Daphnis and have just lapped the moon and are showing the effects of its gravitational perturbations. Meanwhile, particles at the outer edge of the Keeler Gap and to the lower right of Daphnis were last lapped by Daphnis many orbits ago, so those perturbations have been damped out by collisions between the ring particles. Above and to the left of Daphnis, the effects of its gravity can be seen in wispy, wavy features as Daphnis has just lapped those particles. See also chapter 5. While there are more than a dozen gaps in Saturn's rings, Daphnis is one of only two moons detected in any of these gaps. Image Credit: NASA/JPL/SSI.

This brings us to the question of how moons form: when do particles stick together to form a larger object, eventually accreting enough material to be a moon, alone in its orbit, and why do the countless particles of Saturn's rings, colliding thousands of times each year for millions, if not billions of years, stubbornly refuse to accrete into moons? The gravitational force that would bind meter-sized ring particles to each other is incredibly weak: the weight of one such ring particle lying on another is about the same as the weight of a post-it note on the Earth. If those particles were alone in the Universe, even that feeble force would be enough to bind them together. But the ring particles are orbiting Saturn at close proximity, and particles in smaller orbits travel faster than those in larger orbits as a natural

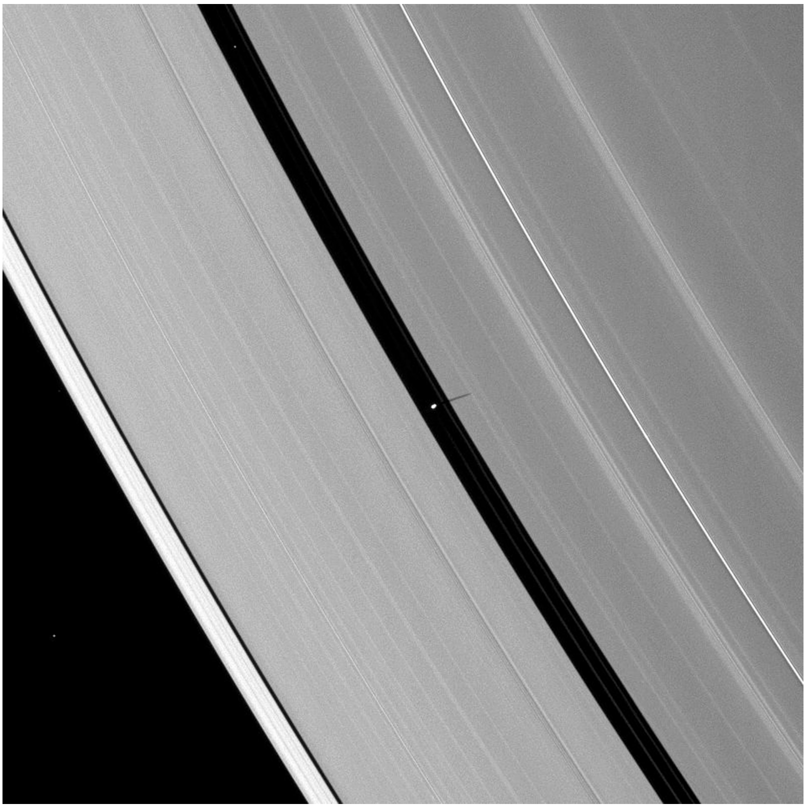

Figure 3.5. This striking image of the outer edge of Saturn's A ring shows the moon Pan in the center of the Encke gap, casting a shadow on the neighboring ring material (the thin dark line extending to the right of the moon). This image was taken by Cassini on May 2, 2009, a few months before the rings were edge-on to the Sun. The shadow cast by Pan here is like the long shadows cast just before sunset on the Earth. When the shadow is much larger than the object, it makes it easier to measure the dimension of the object from precise knowledge of the geometry of the image. Image Credit: NASA/JPL/SSI.

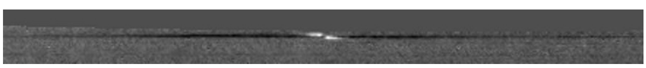

Figure 3.6. This image shows a disturbance in the rings caused by a small moonlet orbiting within the rings, invisible at the resolution of this image. The object, at the center of the propeller-shaped enhancement in ring brightness at the center of the image, is at most a few hundred meters across, large enough to clear away ring particles from its immediate vicinity, but not large enough to open a complete gap, like Daphnis does in the Keeler Gap (figure 3.4). Image Credit: NASA/JPL/SSI.

consequence of how the strength of gravity between two objects depends on their separation. This is why Saturn, which is 9.5 times further from the Sun than the Earth, takes almost 30 years to orbit the Sun. If it orbited at the same speed as the Earth, it would take 9.5 years to orbit the Sun because its orbit is 9.5 times larger. Two neighboring ring particles orbit Saturn at slightly different speeds, and that difference is enough to overcome that featherweight gravitational attraction between the particles. Instead of sticking together, they drift apart. The reason that there are both rings and moons at Saturn and the other giant planets, is that this difference in orbital speed is larger when the orbits are small. Beyond a certain distance from the central object, the difference in orbital speeds is small enough that the gravitational force between particles can overcome it and the particles stick to each other. Thus, we see moons far from a planet, and rings close to a planet. At Saturn, the outer reaches of the rings are at the transition where accretion can take place, and we see a mix of rings and moons (figures 3.4 and 3.6).

The region close to a planet (or star) where accretion is inhibited is called the *Roche zone*, and its precise size depends on the density of the particles and their relative sizes, but it is approximately 2.3 times the size of the planet (figure 3.7). With the exception of faint, tenuous rings made up of dust particles that rarely collide with each other, all planetary rings lie within their planet's Roche zone. The difference in orbital speeds for objects in different orbits is related to what produces tides on the Earth: they are both the result of how the force of gravity between two objects diminishes as the distance between them increases. The Earth's oceans, being large bodies of liquid, are distorted by a small amount by this tidal force from the Moon. As the Earth rotates beneath the Moon, the bulge in the shape of the ocean slowly washes up and down the beach giving us high tide and low tide. We ourselves, however, also live within the Earth's Roche zone, and not only are we not torn apart by the tidal force, we do not even perceive it. The tidal force only wins out against the even weaker gravitational force between two small objects. Place two boulders side by side on the surface of the Earth and they will happily stay there, held in place

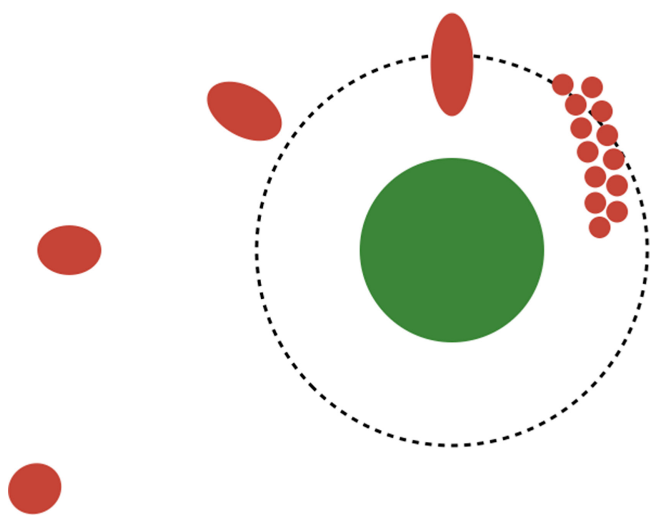

Figure 3.7. Far from a planet, the tidal force is weak, and a moon or comet is not distorted much because the gravitational force exerted on the moon varies by only a small amount across the moon. When the separation between the objects is smaller, the difference in the gravitational force across the moon is larger, and there is a larger tidal distortion of it. Within a certain distance of the planet, the *Roche limit*, an object with no internal tensile strength will break apart.

by the combination of the Earth's gravity and the force of the ground pushing up on them. But place those two boulders in orbit, so that gravity—between the boulders and the Earth and between the boulders themselves—is the only force acting on them, and they will gradually drift apart in their orbits, with the inner one eventually circling around the Earth to lap the outer one. Thus, moons can exist inside the Roche zone, it's just difficult for them to form there. But take a moon that formed outside the Roche zone and move it inward, and, unless it is either very large or structurally very weak (or both), it will remain a moon inside the Roche zone.

This leads to two basic ideas for how the rings can form: they are left over from the formation of the planet itself; or they are the debris left over from the destruction of some large object such as a moon or a wayward comet that found its way inside the Roche zone. Both hypotheses present serious challenges for the case of Saturn's rings due to their sheer size. Pictures of the rings show how much area they cover, but tell us little about how massive they are, just as a distant picture of a large, opaque sheet could be a picture of a sheet of paper or of a 10 m thick slab of lead. Pictures show us the surface, like the façades of buildings on a movie set, without revealing how much substance lies beneath. Fortunately, we have other means of estimating the masses of rings, and while there is still considerable uncertainty, the mass of Saturn's ring system is likely at least 1000 times more than the mass of all the other rings in the solar system combined. And this has made explaining their existence roughly 1000 times more complicated.

The small amounts of material in the ring systems of the other planets can be accounted for by the fragmentation of small moons when hit by a comet, for example, or the gradual erosion of moons by the constant hail of micrometeoroids in interplanetary space. Indeed, the latter process is what produces the G ring of Saturn (figure 3.1), but this ring is just a wispy companion to the massive, bright main rings. The rates of these impacts and the number and sizes of moons available fit nicely with the rings observed at Uranus, Neptune and Jupiter. But to create Saturn's giant ring system, a moon roughly the size of Saturn's moon Mimas (figure 3.8) must have been completely fragmented into ring particles, and since nothing is ever 100% efficient, the progenitor must have been larger still. And since Saturn's ring particles are almost pure water ice, the progenitor must have been as well, or only the outer icy layers of an even larger object with a rocky core were stripped off to form the rings. But, as we've seen with the census of Saturn's many moons, larger objects are less common than small objects. Furthermore, they are more difficult to break up through catastrophic impact by an asteroid or comet. Although they present a larger target area to interloping comets that might smash them to smithereens, their greater size also results in a greater gravitational binding energy: all that mass holds the thing together even more powerfully than the physical strength of ice and rock it is made of. And the creation of the rings by the tidal disruption and capture of a comet would require an unusually large comet. Calculations and numerical simulations of these processes indicate that it is very unlikely to have occurred after the era of planet formation itself ended some 4.5 billion years ago.

There is a model, dubbed the 'Nice model' after the observatory in Nice, France, (though it is also a nice model) that posits a major shake-up of the solar system

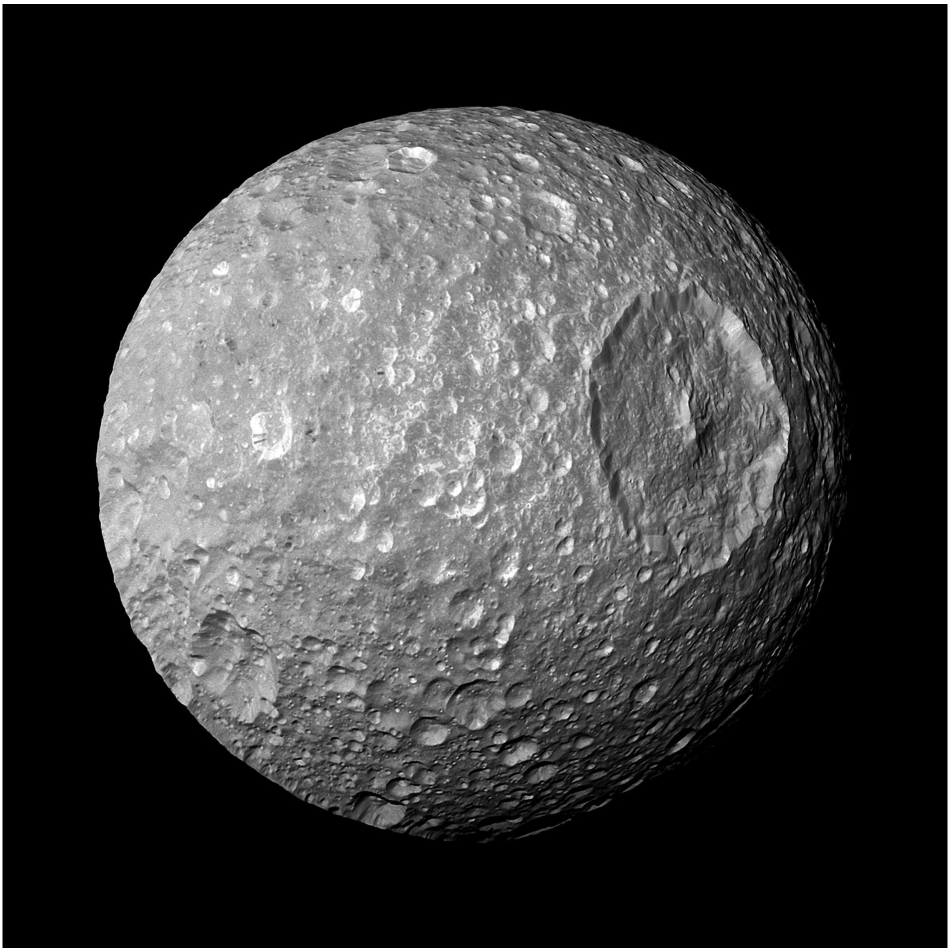

Figure 3.8. Mimas, 396 km across, is the 7th largest moon of Saturn. This figure is a mosaic created from six images taken on February 13, 2010, from a distance of 50 000 km in visible light with Cassini's narrow-angle camera. The images were re-projected to provide this global perspective. The large Herschel crater at right is 130 km in diameter and gives Mimas the nickname 'the Death Star moon'. If the object that hit Mimas to make this crater had been somewhat larger it would have destroyed the moon. Image Credit: NASA/JPL/SSI.

leading to a large increase in the number of major impacts about 3.8–3.9 billion years ago. This epoch, sometimes called the *Late Heavy Bombardment* (LHB), could have produced the impacts or capture scenarios necessary to create Saturn's rings after the era of planet formation. After that time, however, it becomes increasingly difficult to create a scenario for the formation of Saturn's rings that doesn't require a very unlikely event, and even the existence of the LHB itself remains controversial. The difficulty of forming the rings after the rate of big collisions settled down, whether that was 3.8 or 4.5 billion years ago, would not be such a big deal if not for a long list of clues that indicate that Saturn's rings date from only about 0.1 billion (100 million) years ago. We'll return to these in chapter 5. For the moment, then, in spite of the wealth of knowledge about Saturn's rings provided to us by Cassini's observations, the precise manner of the origin of the rings remains, like their age, uncertain and a topic of active research. Cassini's final orbits in the summer of 2017 will provide us with an accurate measurement of the mass of the rings, and this will place a tight constraint on models of their origins.

The formation of Saturn mimicked, on a smaller scale, the formation of the solar system. The planet formed at the center of a disk of gas and solid particles. The solid particles orbit the planet according to the law of gravity, with the orbital speed decreasing with increasing distance from Saturn. The gas, on the other hand, is like an extended atmosphere of the planet and moves at a different speed. This difference in speeds results in friction between the solid particles and the gas which causes the solid particles to spiral in toward the growing planet. As they migrated inward, particles were able to accrete to form moons as long as they were outside the Roche zone. Interlopers from interplanetary space were captured in the cloud of gas and continued to grow there by collisions with other particles in this 'sub-nebula' disk. A few tens of millions of years after the initial formation of the Sun the intensity of the *solar wind*, the normal flow of electrons and protons away from the Sun, increased dramatically and blew the remaining gases out of the solar system, including the sub-nebular disks of Saturn and the other giant planets. This effectively ended the formation of the planets and stopped the migration of proto-moons inward towards Saturn. Just how the set of moons Saturn had at that time compares to the present distribution is not entirely clear. It is possible that there were many more small moons that over the eons have been disrupted to create rings. It is also possible that a primordial ring system itself gave birth to some of the small icy moons. We'll return to this intriguing possibility in chapter 5. The origins of Saturn's moons may be as diverse as the moons themselves. Next we turn our attention to the icy worlds at Saturn as they are now.

Further reading

The 'Nice model' was originally proposed in a series of papers (Gomes *et al* 2005, Tsiganis *et al* 2005, Morbidelli *et al* 2005) by researchers working at the observatory in Nice, France. A model for formation of moons from the rings was proposed by Charnoz and colleagues (2010).

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Chapter 4

A menagerie of moons

Saturn's moons fall into a number of different categories, as we've seen in chapter 3. Titan, the largest moon, would be a planet were it orbiting the Sun instead of Saturn, and we'll discuss it in detail in chapter 6. The remaining smaller moons exhibit a variety of unique and surprising features, each of which traces back to a physical process in the system. In this chapter we describe the processes that have shaped and altered the moons, looking at specific examples that highlight these processes, but not all of the five dozen moons.

4.1 The inner mid-sized icy moons

The four large satellites of Jupiter, the Galilean satellites, fit well in a model of moon formation that mimics the formation of the planets as a whole, but on a smaller scale centered on a planet instead of the Sun. Saturn's satellite system presents no such regular grouping that can be readily explained that way. The largest moon, Titan, may well have formed analogously to the Galilean satellites, but the remaining regular moons[1] may have a variety of origin stories. We will visit Titan, a world larger than the planet Mercury, in chapter 6. Next in size from Titan is a group of regular moons referred to as the mid-sized icy satellites: Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion and Iapetus. Enceladus, Hyperion and Iapetus have remarkable characteristics that are discussed in detail below. We begin, for some context, with the remaining four. Their surfaces are marked primarily by craters with varying degrees of tectonic features due to ancient stresses associated with tides and the original freezing of the moon from its initial partially molten state. These follow, more or less, our expectations for medium-sized icy moons in the outer solar system. Proceeding outward from Saturn they are Mimas, Tethys, Dione, and Rhea, the second-largest of Saturn's moons (figure 4.1).

[1] Regular moons are those on prograde orbits that are nearly circular and close to Saturn's equatorial plane. The irregular moons are likely captured from interplanetary space, as discussed in chapter 3.

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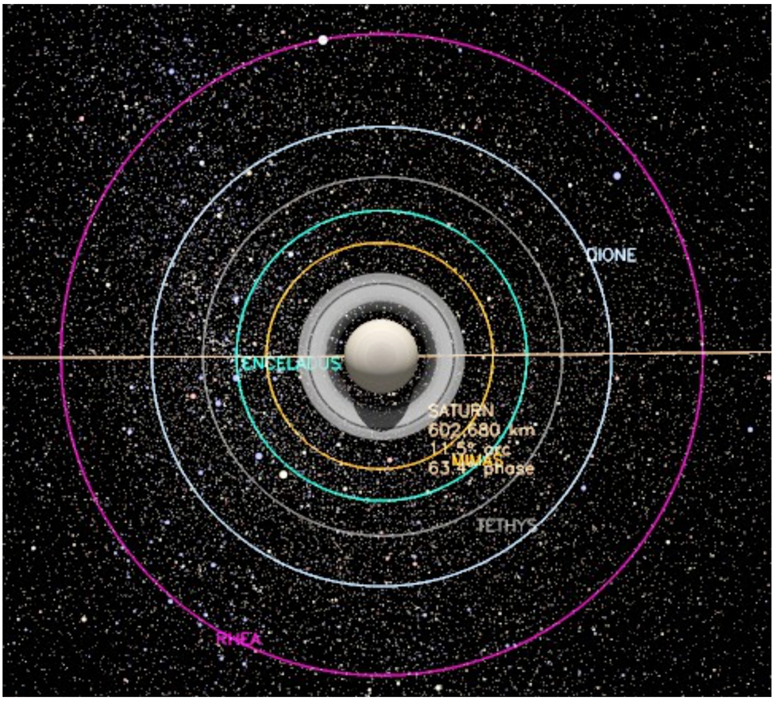

Figure 4.1. Saturn, its main rings, and the orbits of the inner mid-sized icy moons are shown to scale in this schematic.

Each of these moons is large enough for its gravity to deform it into a roughly spherical shape, but not so large that they have not long ago lost the heat leftover from their formation. This heat of formation, the relic of the kinetic energy of all the pieces that collided with each other to make the moon in the first place, together with the energy released from the decay of any radioactive materials in the moon, is what drives geologic activity, such as volcanoes and plate tectonics on the Earth. Larger objects retain their heat longer than smaller ones because, although they have a larger surface to radiate heat to space, the stored energy in their interiors is larger still. A baked potato stays hot longer than peas on your dinner plate for the same reason. What we might expect, then, for these four moons is an appearance similar to our own Moon: heavily cratered with perhaps some relics of ancient geologic activity.

4.2 Impacts and craters

All objects in the solar system are hit by debris left over from the period of planet formation. We refer to these objects now, generically, as either comets if they are icy objects in the outer solar system, or asteroids if they are primarily rocky or metallic objects in the inner solar system. An impact by a 10 km asteroid 65 million years ago ended the Cretaceous period and the existence of most species on Earth, but the crater from that impact is now buried beneath the ocean floor off the Yucatan peninsula. So, while that was a relatively large and recent (compared to the age of the planets) impact, the visible surface traces of it have long since been erased by

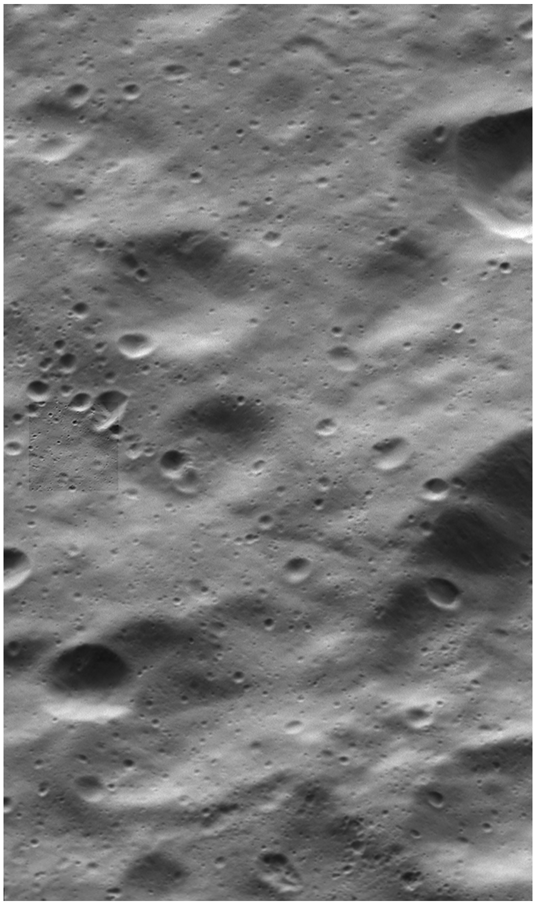

Figure 4.2. This view of ancient cratered terrain on Saturn's moon Dione was taken from a distance of 537 km and has a resolution of 32 m/pixel. The high-resolution inset on the center-left of the image has a resolution of 3 m/pixel. Small craters greatly outnumber larger craters, some of which are now only faintly visible as partial circular depressions. Image Credit: NASA/JPL/SSI.

tectonic and erosional processes on the Earth. Moons without an atmosphere don't have erosion to cover up their impact craters, and generally any geological activity ceased long ago. Their surfaces thus provide an important record of their bombardment history, which in turn is linked to the population of asteroids and comets in the solar system and the evolution of that population over the age of the solar system. The cratered terrains of these icy moons are witness plates to the history of Saturn's corner of the solar system (figure 4.2).

There has been extensive research on the relationship between the size of a crater and the properties of the impact that produced it[2]. The mass and speed of

[2] Many of these studies are based on studies of craters produced by bombs. This is a valid application of those data, because an interplanetary impactor delivers energy in an even more concentrated form than any conventional explosive.

the impactor are the two most important properties, but the densities of both the impactor and the target surface also play important roles. When we observe the surface of a moon such as Mimas or Dione (figure 4.2) we see a distribution of crater sizes, with smaller craters more prevalent than larger ones. This reflects primarily the greater abundance of smaller objects in the solar system than larger objects. For each factor of 10 increase in the size of a comet or asteroid there is roughly a factor of 300 decrease in their abundance. If you smash a rock with a hammer repeatedly you will find a similar result: many more small pieces than large pieces. There are significant deviations from this general rule based on the population of objects (for example, the main asteroid belt compared to the vast reservoir of comets beyond Neptune known as the Kuiper belt, or the more-distant Oort Cloud reservoir of comets), and this relationship does not hold over all sizes. Nevertheless, if all other things were equal, we might expect the same distribution of crater sizes on a moon of Saturn, namely 300 1 km craters for each 10 km crater. Of course all other things are far from equal.

Craters are formed on a moon when an interplanetary impactor happens to hit it. These impactors may be icy or rocky, and come in a range of sizes, from the size of a grain of sand up to objects tens of km across. When these objects hit the Earth, unless they are large enough to survive being vaporized from friction with the atmosphere, they burn-up high in the sky, creating a meteor trail. But when they hit an object with no atmosphere, such as our Moon, or Rhea, for example, they smash into the surface at speeds of several km s^{-1} up to tens of km s^{-1}. The amount of energy delivered to the surface this way is like a bomb going off. Impacts faster than 2.89 km s^{-1} (which is the case for most cratering impacts onto moons in the Saturn system) produce more energy than if the entire impactor were converted to TNT and detonated. Usually these impactors excavate a bowl-shaped depression (the crater), while sending a shock wave into the interior of the moon and sending a spray of high-speed *ejecta* (vaporized and particulate debris produced in the impact) out in a conical fan from the crater rim. Cratering impacts on large objects, such as Rhea, produce ejecta that falls back down on the surface producing a pattern of rays emanating from the crater (figure 4.3). This is because the ejecta travels at a much slower speed than the impactor, and the gravitational pull of a large body prevents this slow-moving material from escaping to space. The ejecta has two complicating effects: it buries and obscures older, small craters, and it can create new *secondary craters* when it falls back down onto the surface. Each of these processes complicates the effort to relate the distribution of crater sizes to the impact history of a moon.

We know something about the current size distribution of impactors in the Saturn system from astronomical observations of asteroids and comets, but our knowledge is limited by our ability to see small objects at great distances from the Sun[3]. A useful rule of thumb is that the diameter of a crater is about 10 times the diameter of the

[3] Observations of small distant objects are even more difficult than one might expect: they are difficult to see because of their great distance from us, but even more so because of their great distance from the Sun which means they are only very faintly illuminated. Even at Saturn, relatively nearby compared to comets in the Kuiper belt, the illumination from the Sun is on average only 1.1% of what we have on Earth. Finally, many objects in the outer solar system are extremely dark, reflecting only 5–10% of incident sunlight.

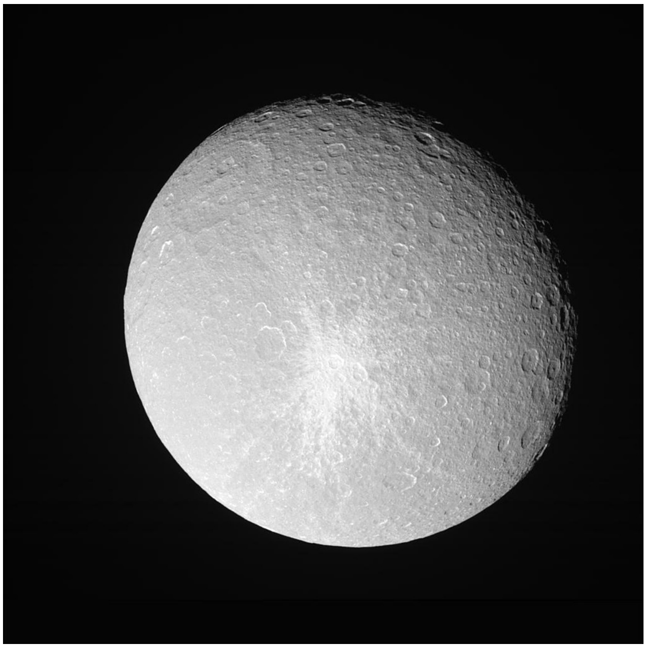

Figure 4.3. This image of Rhea shows the crater Inktomi and its prominent butterfly-shaped pattern of bright ejecta rays. The large impact basin Tirawa can be seen at upper left. Image Credit: NASA/JPL/SSI.

object that made it. So a 10 km crater is produced by the impact of a 1 km object. A primary source of impactors for the Saturn system is the Kuiper belt, more than 3 times further from the Sun than Saturn itself. We have only a rough idea of the population and distribution of sizes of such small comets because we can typically only see them when they happen to migrate closer to the Sun (and the Earth)[4]. We have a more complete picture of the size distribution of asteroids, and we have learned a lot about the size distribution of impactors in the ancient solar system from observations of the distributions of crater sizes on the Earth's Moon. Critically, for the Moon, the Apollo astronauts returned rock samples whose ages have been accurately measured in terrestrial laboratories using radioactive dating techniques. We lack such an absolute calibration for chronology of the Saturn system. Nevertheless, the combination of crater counts on other worlds and observations of comets and asteroids throughout the solar system provides some reasonable estimates for the population of interplanetary impactors passing through the Saturn system.

One of the discoveries of the Voyager missions, confirmed by Cassini, is that this population is inconsistent with the distribution of craters on Saturn's moons. Here's how we know this. Potential impactors (comets and asteroids) in interplanetary space are on orbits around the Sun, just like Saturn is. If an impactor comes close to Saturn it will be attracted by Saturn's gravitational pull and pass even closer to

[4] This migration occurs as a result of gravitational perturbations from the planets, other objects in the Kuiper belt, and even other stars in the Galaxy.

Saturn than it would if Saturn had no gravity. Saturn's gravity thus increases the number of impactors that pass within a certain distance of the planet, say the outer edge of the rings or the orbit of one of its moons. This *gravitational focusing* of the interplanetary impactor population is larger close to Saturn, and fades away at large distances. Thus we would expect a greater flux of impacts from comets and asteroids on the inner moons such as Mimas and Rhea than the outer moons such as Iapetus and Hyperion. Saturn's gravity also accelerates these impactors so that they hit their targets at a faster speed than they would if Saturn had no gravity. This effect is also strongest for the inner moons close to Saturn. To hit them, in effect, a comet must fall further toward Saturn than it would if it hit an outer moon, and as it falls toward Saturn it picks up speed. Thus we expect both more-numerous and more-energetic impacts on the inner moons, leading to denser crater fields and larger craters on the inner moons. Instead we see the greatest number of large impact basins, five larger than 300 km, on Iapetus, the most distant of the mid-sized icy moons, and only a total of seven such basins on the remaining four heavily cratered mid-sized moons combined. One such basin is shown in figure 4.4. Based on our knowledge of the

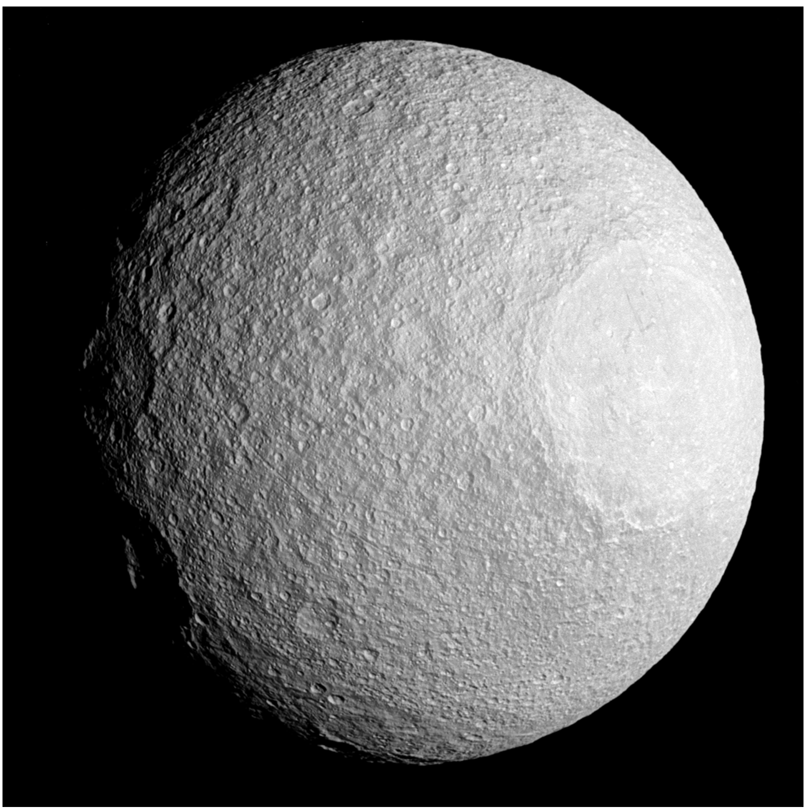

Figure 4.4. This view of Tethys, taken by Cassini on April 11, 2015, shows the large Odysseus impact basin on the right. This crater has a diameter of 450 km, nearly half the diameter of Tethys itself, and is one of the largest impact basins on any of the Saturnian moons. Tethys has a heavily cratered terrain with almost no signs of geological activity. Careful counting of all the craters in images such as this provides clues to the identity of the objects that hit the moons and the history of Saturn and the solar system. Image Credit: NASA/JPL/SSI.

interplanetary impactor flux and the effects of gravitational focusing we would expect none at all on Iapetus, and roughly only one per moon for the remaining satellites (Dones *et al* 2009).

4.3 Synchronous rotation

Another important contributor to the speed of an impact is the motion of the moon itself in its orbit around Saturn. Most moons in the solar system, including our own as well as almost all the moons of Saturn, rotate synchronously with their orbital motion. When a moon is in synchronous rotation, the length of a day on the moon is equal to the time it takes it to complete one orbit of its planet. This is why on the Earth we always see the same face of the Moon. This synchronization of a moon's spin period with its orbital period is not a coincidence. The same tidal force that gives us ocean tides on Earth and prevents ring particles from accreting into moons at Saturn (chapter 3) produces this synchronous rotation. Such moons are *tidally locked* in their orbits. The tidal force stretches the moon, ever so slightly, and this deformation removes rotational energy from the moon until it settles into a rotation rate so that it is always stretched along the line connecting the moon to the planet. After this synchronization no further changes in the deformation take place (figure 4.5). They thus have a *leading hemisphere* that is *always* facing in the direction of its orbital motion, and a *trailing hemisphere* facing in the opposite direction. Impactors that hit the leading hemisphere of a moon hit it at a much greater speed than those that hit the trailing hemisphere because the orbital velocity of the moon adds to whatever velocity the impactor had. Those that hit the trailing hemisphere must catch up to the moon, in a sense, and hit the surface more gently and produce a smaller crater for the same size impactor.

Impactors flying through the Saturn system from interplanetary space hit the leading hemispheres of moons more frequently and violently than they hit the trailing hemispheres, leading to larger craters on the leading hemisphere. But this is

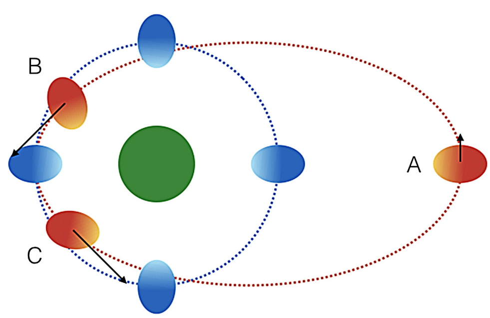

Figure 4.5. The blue moon is on a circular orbit. Tidal forces have stretched it, and it becomes tidally locked into synchronous rotation so that it keeps the same face always pointing toward the planet (green). The red moon is on a highly eccentric orbit (exaggerated here for clarity). At point A it is moving slower and it is easier for the moon to maintain its orientation as it orbits the planet. At points B and C, when it is closer to the planet, it is moving faster (arrow lengths indicate speed) so it must rotate faster to maintain its orientation to the planet. This changing orbital speed introduces a wobble in the moon's rotation.

not what is seen on Saturn's moons. The lack of a clear asymmetry in the crater distributions between the leading and trailing hemispheres together with the mismatch between the size distribution of craters and the size distributions of asteroids and comets suggests that many of the craters were not produced by impactors that were orbiting the Sun but rather by objects that were orbiting Saturn. It seems, in other words, that many of the craters on Saturn's moons were made by impacts by other moons or fragments of other moons.

The system of satellites at Saturn has had a violent and dramatic history. The number of moons has likely changed significantly, with new moons captured into orbit and then broken apart either by impacts from comets or collisions with other moons in the system. The irregular satellites come in groups, with the moons in a group having similar orbits indicating that they are fragments of a single larger progenitor, broken apart by collision with another moon or an interplanetary interloper. Some regular satellites certainly suffered the same fate. The debris from these collisions in turn rained down upon the larger moons. Such a cataclysm may explain the existence of the ring system itself, as we will see in the next chapter.

4.4 Icy satellite tectonics

There are also some intriguing pieces of evidence of past geological activity on some of the mid-sized icy satellites. Aside from cratering, the surfaces of moons can be altered by tectonic stresses. These can be caused by changes in the amount of tidal stretching of a moon as its spin state and orbit evolve (figure 4.6) and by changes in the volume of the moon as it cools and freezes. Very large impacting events can also cause global fractures on the surface of a moon. There is also the possibility of *cryovolcanism*, or the eruption and flooding of the surface by water from a liquid reservoir beneath the surface. With the exception of Enceladus, which we'll discuss in detail below, the other icy moons have long since frozen, so their tectonic features are billions of years old. This is confirmed by the density of craters on top of the tectonic features, though we cannot place precise ages on features without a sample for absolute radiometric dating. There is another important consequence of the tidal interaction between moon and planet discussed above (figure 4.5). The orbit of the moon gradually evolves as well, becoming larger for moons whose orbit is longer than a Saturn day[5]. As the orbit expands, the strength of the tidal deformation decreases resulting in changes to the stress patterns on the moon. This is likely the explanation of the system of fractures on Dione (figure 4.7).

4.5 Interactions with the magnetosphere

Cassini's cameras extend to wavelengths far beyond what the human eye can see in the familiar visible-light images shown above. Seen in the far-infrared portion of the

[5] All known moons of Saturn have orbits longer than a Saturn day. The Earth's Moon is also undergoing this tidal orbital evolution, currently moving away from the Earth at rate of 3.8 cm/year. The rate is much faster when the moon is closer to the planet. Mars's moon Phobos orbits in less than a Mars day, and as a result its orbit is decaying. Phobos will one day crash onto Mars, probably within the next 100 million years.

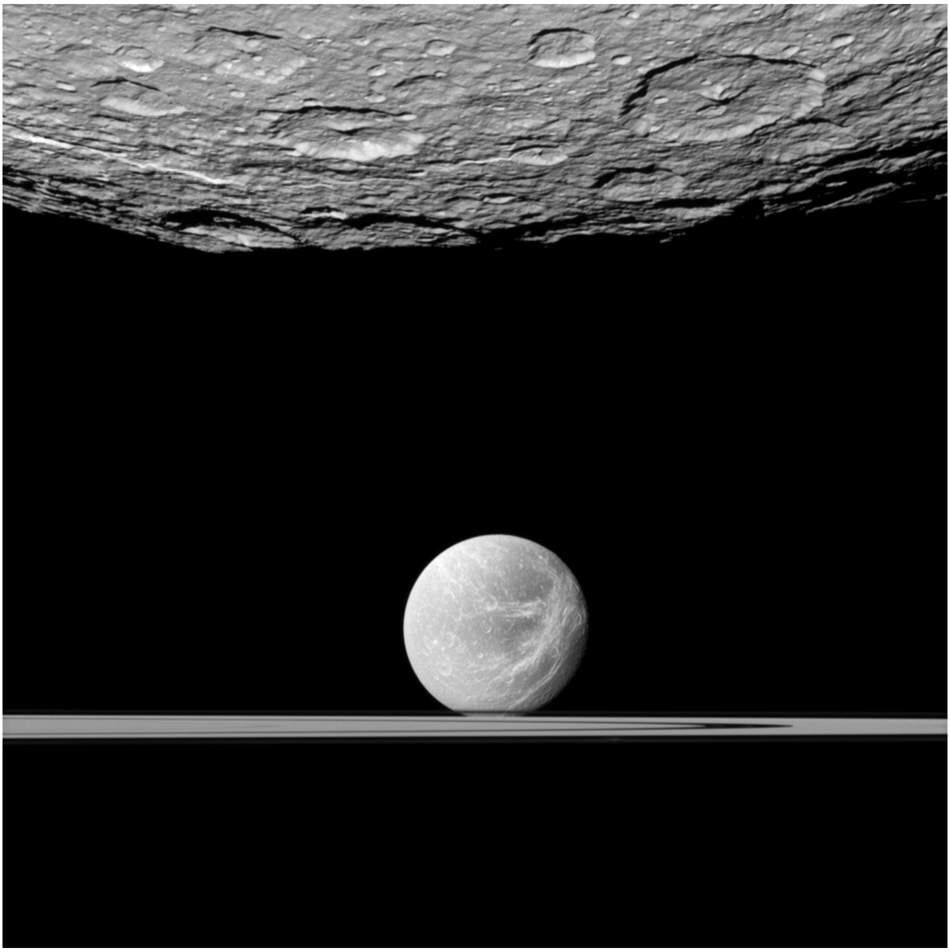

Figure 4.6. One of the many stunning 'photo-op' images taken by Cassini, this 2011 image shows Dione's 'wispy terrain' and the rings in the distance with the heavily cratered surface of Rhea in the foreground at a resolution of 358 m/pixel. Larger craters have a central peak formed when the surface, molten by the impact, splashes back upwards. A similar phenomenon can be seen by dropping a Cheerio in some milk. Image Credit: NASA/JPL/SSI.

spectrum, where the light we see is emitted by the surfaces rather than reflected sunlight, Mimas and Tethys exhibit a striking 'Pac-Man' appearance (figure 4.8). Here, bright yellow features are warmer than dark blue features, and the false-color rendering of these images with yellow indicating higher temperatures than blue features results in an uncanny resemblance to the video arcade game of the 1980s. These temperature maps were completely unexpected. Without an internal heat source, the surface should be warmest where it receives the most direct sunlight, and cool gradually away from that point. The Pac-Man temperature patterns are striking in that they are independent of the position of the Sun, and the boundary between cold and warm temperatures is an abrupt, sharp V-shaped feature. Either there is

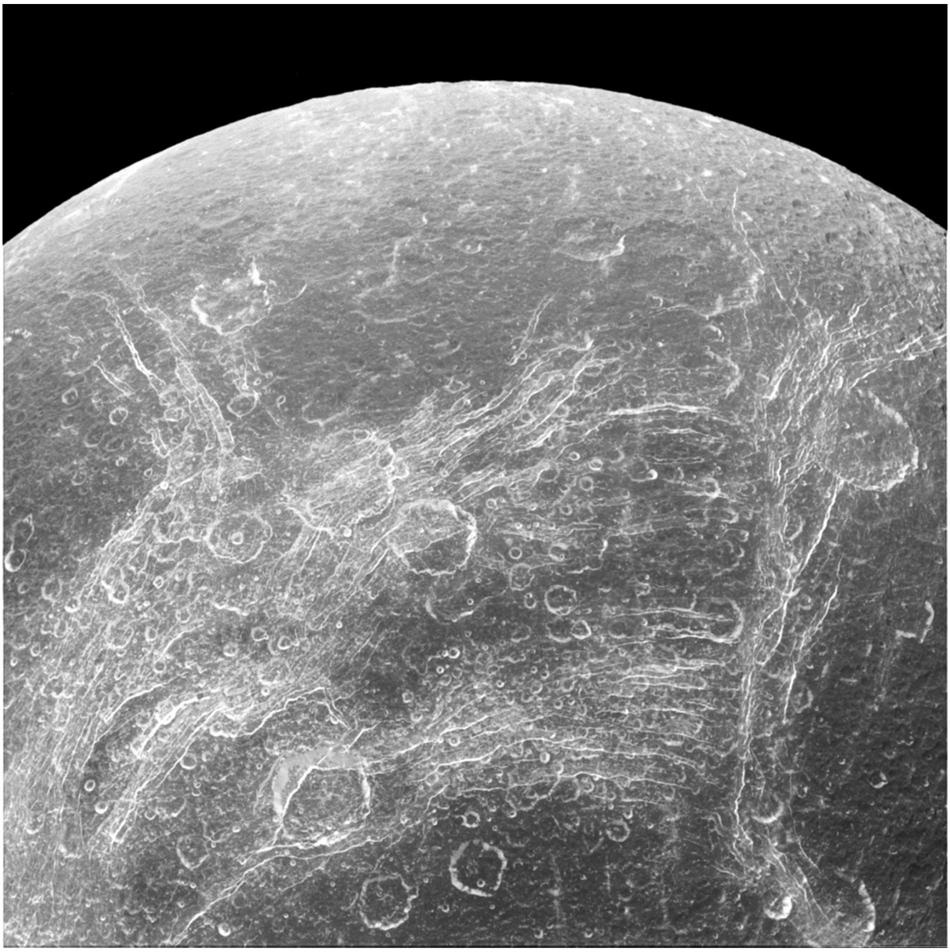

Figure 4.7. Chasmata or 'wispy terrain' on Dione are bright icy cliffs likely due to stresses resulting from changing tidal deformation as the orbit of Dione evolved over time. Image Credit: NASA/JPL/SSI.

something heating up the warmer regions, or there is something different about the surface that causes one region to cool much more quickly than the other. The orientation of Pac-Man provides a clue: the cool regions are on the leading hemispheres of the moons. This suggests that it may be related to something hitting that side of the moons and altering it so that it doesn't heat up as much in the daytime. That something turns out to be energetic electrons in Saturn's magnetosphere.

In addition to being pelted by comets, asteroids, or other moons, the moons are bombarded by charged particles. Like Earth, Saturn has a magnetic field that blocks and diverts the electrons and protons flowing outward from the Sun, the so-called solar wind. The magnetic field traps these charged particles, charged particles liberated from the upper atmosphere of Saturn and Titan by high-energy solar photons, and atoms knocked off the surfaces of the moons and subsequently ionized

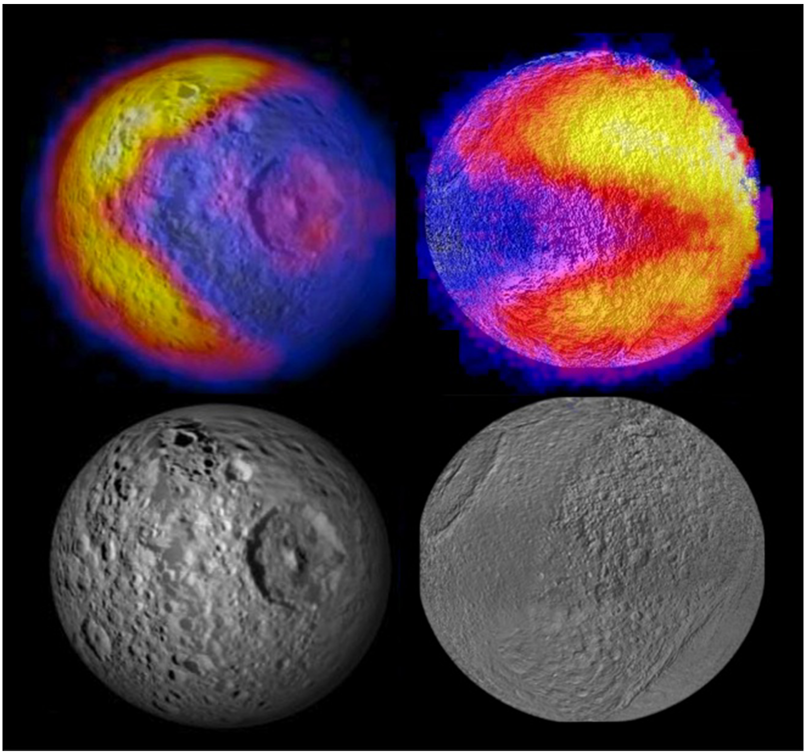

Figure 4.8. Mimas (left) and Tethys (right) seen in infrared light from Cassini's CIRS instrument (top) and visible light (bottom). In the upper images, yellow corresponds to the highest temperatures, and blue regions are about 20 °C cooler. Image Credit: NASA/JPL/GSFC/SWRI/SSI.

by sunlight. These negatively charged electrons and positively charged ions spiral around the magnetic field and 'bounce' back and forth around the equatorial plane of Saturn as they do so due to the electromagnetic force. This force causes charged particles to follow curved paths perpendicular to the direction of the magnetic field. Understanding this complicated gyrating motion frequently requires some complicated mental gymnastics (figure 4.9).

The magnetic field rotates with Saturn itself, which has a day that is about 10 h long. The moons take longer than 10 h to orbit Saturn, so the magnetic field sweeps by the moons from behind their trailing hemispheres. If the electrons and protons were moving only with the magnetic field, this would mean they bombard the trailing hemispheres of the moons. The slower-moving or 'cold' protons and electrons do just that: they preferentially bombard the trailing hemispheres of the satellites as the magnetic field sweeps by them.

The more energetic a charged particle is, however, the larger is its radius of gyration around magnetic field lines (figure 4.9). While an energetic electron is traveling along its spiraling path, its distance from Saturn can vary by a large amount, so the strength and geometry of the local magnetic field it is moving through also changes. As a result, it experiences a varying magnetic force that has

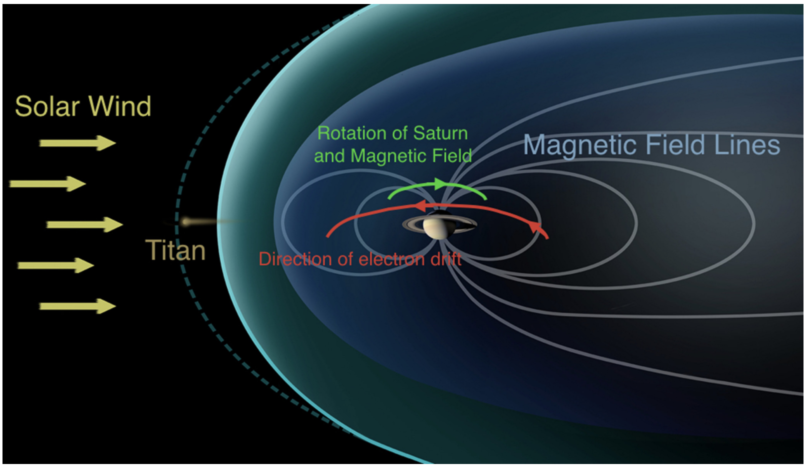

Figure 4.9. This schematic of Saturn's magnetic field shows the solar wind compressing the magnetic field on the left, temporarily leaving Titan outside Saturn's magnetosphere. Electrons gyrate around magnetic field lines and 'bounce' up and down along the lines between the north and south polar regions. They are carried around with the magnetic field which rotates with Saturn (green). The size of the spiral and the speed of the drift depend on the particle's energy. High energy electrons have large gyrations which result in an additional 'drift' in the opposite sense of the rotation of the magnetic field (red). Based on image from NASA/JPL-Caltech.

the net effect of causing it to drift around Saturn in the *opposite* direction of the rotation of the magnetic field. This only happens for energetic electrons. Unlike the slow-moving charged particles, these energetic electrons preferentially hit the leading hemisphere of a moon. Low-energy electrons and ions move on much smaller, tighter spirals that don't experience enough variation in the magnetic force to produce a significant drift. The motion of positively charged particles is in the opposite sense as the electrons, so they drift around Saturn in the prograde direction, moving past the trailing hemisphere of the moon even faster than they would in the absence of a drift.

This complex dance of charged particles is likely the cause of the Pac-Man features on Mimas and Tethys. By bombarding the leading hemispheres of these moons, high-energy electrons physically alter the icy grains on their surfaces, compacting a relatively porous layer of particles into hard-packed ice. This hard-packed surface takes longer to heat up in the daytime because it conducts heat from the Sun into the interior of the moon more efficiently than a fluffy porous surface does. As a result, the temperatures in the mouths of the Pac-Man features remain relatively constant while the rest of the moons' surfaces have large daily fluctuation in temperatures, producing the distributions of temperatures seen in figure 4.8.

4.6 The curious case of Hyperion

A quick glance at Hyperion is enough to tell us that there is something peculiar about this moon (figure 4.10). Like the other small moons, it is not spherical in shape. Its small size means its gravity is too weak to deform the object into a spherical shape. It is the appearance of its craters that make it stand out. Hyperion

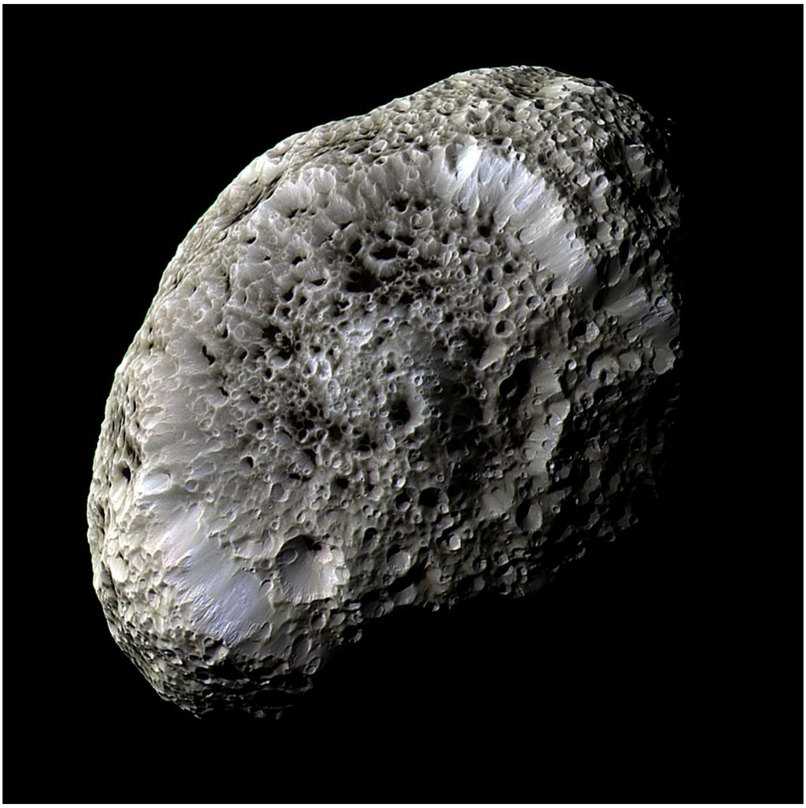

Figure 4.10. This false-color view of Saturn's moon Hyperion was obtained during Cassini's close flyby on September 26, 2005. The spectrum of Hyperion is reddish, though the moon appears gray to the eye. Color differences are enhanced here to highlight what could be compositional differences between cliffs and crater bottoms. This is a composite made from images taken through infrared, green, and ultraviolet filters. The resolution is 362 m per pixel, and the moon is 360 km across in the long dimension. Image Credit: NASA/JPL/SSI.

looks so much like a loofah, in fact, that the paper from the Cassini imaging team describing Hyperion's craters in the prestigious and staid scientific journal *Nature* is titled 'Hyperion's sponge-like appearance' (Thomas *et al* 2007). Like many of Saturn's moons that orbit near the rings, Hyperion's density is quite low, only about 0.54 g cm^{-3} (water has a density of 1.0 g cm^{-3}), though Hyperion is on a very distant orbit from Saturn. Those so-called ring moons, however, are much smaller, and owe their low densities to the accumulation of thick coatings of loosely packed small particles on the surface. Hyperion's surface does not appear to have such a coating. Phoebe, which is slightly smaller than Hyperion, has a density of 1.6 g cm^{-3} (and a shape that is much closer to a sphere). By making reasonable assumptions about the fraction of ice and rock in the moon, the low density of Hyperion means that its porosity is greater than 40%. That is, almost half of Hyperion is empty space. Like a sponge.

This low density means that it has a small mass for an object of its size, so its weak gravity is not able to prevent most impact ejecta particles from simply escaping the moon altogether, never to return. When a crater is formed on Hyperion, it loses most of the ejecta to space. This means that not only is there no production of secondary craters from ejecta falling back onto the surface but also that the surface remains free of the coating of debris from other impacts. On most objects this ejecta coating obscures and eventually covers up older craters. Craters on Hyperion thus maintain a sharper appearance, giving them the appearance of geological youth. Compared to Phoebe (figure 4.11), whose surface is worn and softened by the accumulation of ejecta from its craters, Hyperion's surface looks crisp, clean, and freshly carved as though someone had taken a giant ice cream scoop to it (figure 4.10). Because most craters are bowl-shaped, with roughly the same depth-to-diameter ratio, smaller craters are more quickly buried under fresh ejecta than larger craters. Further, because it is so porous, impactors tend to burrow into the surface, creating slightly deeper craters for the same size impactor on Hyperion than on larger moons.

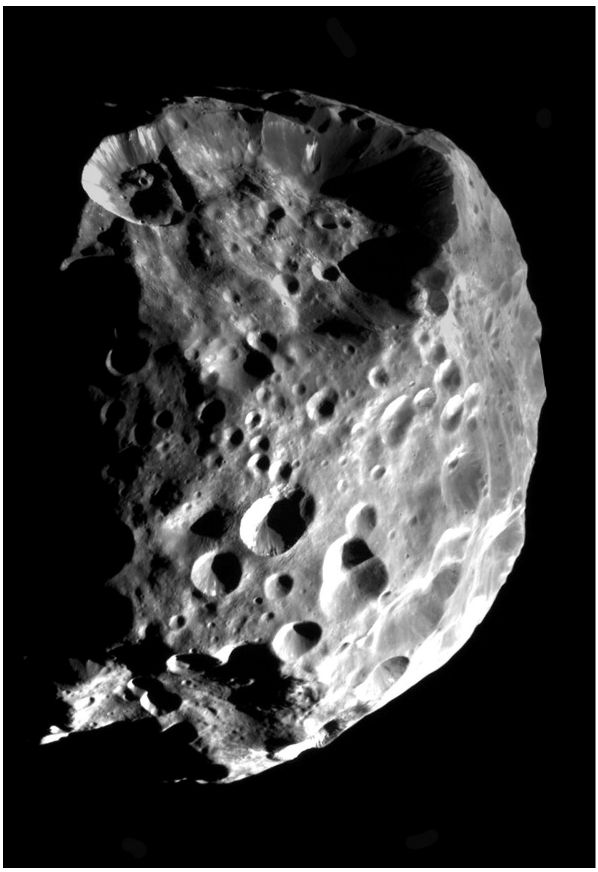

Figure 4.11. This image of Phoebe is at roughly twice the resolution of the image of Hyperion in figure 4.10. In spite of the higher resolution (190 meters per pixel), Phoebe's surface appears softer than Hyperion's due to the presence of worn-down craters. This is the result of older craters being gradually covered up by ejecta from more recent craters, a process that is less efficient on Hyperion due to its high porosity. Image Credit: NASA/JPL/SSI.

Whether Hyperion's high porosity results in the production of less ejecta, faster ejecta, or both, the lack of ejecta coating the surface and the difference in crater morphology due to its high porosity gives it an abundance of mid-sized craters compared to other moons.

Another peculiar aspect of Hyperion is how it spins as it orbits Saturn. Hyperion is the only regular (not captured) moon of Saturn (or of any planet) that is not tidally locked. Its rotation is chaotic which simply means that its orientation in space cannot be predicted ahead of time. In contrast, the other moons maintain a nearly fixed rotation axis whose small wobbles, if any, are periodic and predictable. Hyperion's chaotic rotation is due to the proximity of its orbit to that of Titan, its oblong shape (figure 4.10), the high eccentricity (deviation from a perfect circle) of its orbit (figure 4.5), and that its orbit is in a resonance with Titan. Hyperion's eccentricity is 0.12, meaning that on each orbit of Saturn its closest point to the planet is 12% closer than the average distance, and the furthest distance is 12% further than the average distance. While 12% doesn't sound like a huge amount, it's much larger than that of the other regular satellites, and because it is 12% in both directions, the distance between Hyperion and Saturn varies by about 24% each orbit. A moon on a circular orbit can easily settle into a tidally locked rotation as shown in figure 4.5, where the spin rate and orbital rate are both constant and equal to each other. But if the moon is on a highly eccentric orbit, its rate of motion around Saturn varies with its distance from Saturn each orbit. The tidal locking mechanism, which tries to make the spin rate and orbital rate synchronize, takes much longer than one orbit to change the spin rate. In a sense, Hyperion is constantly struggling to change its rotation rate to match its ever changing orbital rate. The result is a complicated and chaotic tumbling of the moon.

The highly oblong shape of Hyperion, unusual for an object of its size plays an important role as well. The spin of oblong objects is surprisingly complicated. There is a simple experiment that illustrates this. For this experiment, take an object that has different lengths in each dimension, such as this book[6], whose length, width and depth are very different (figure 4.12). If you toss this object in the air with a spin so

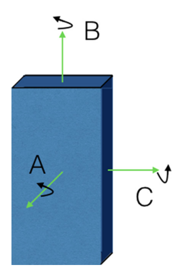

Figure 4.12. An oblong object has three principal axes of rotation. Spins around axes A and B are stable, but around axis C the spin is unstable.

[6] If you are reading this on a cellphone or tablet, the experiment will still work, but take care not to damage your device! If you use a physical book, fasten it shut with a rubber band. If you are reading it on a computer, find something else to throw in the air.

that it rotates around its short axis (A) or its long axis (B), the direction of the axis of rotation remains constant: the rotation is stable. But toss the book in the air with a spin around the intermediate axis (C), and it tumbles. Try it. It's weird.

The reason for Hyperion's large eccentricity, which in turn leads to its struggles to maintain a constant rate of rotation, is the strong gravitational tug it receives from neighboring Titan. The gravitational perturbations from Titan that Hyperion experiences are large, due to Titan's large mass. There is an orbital resonance between Hyperion and Titan: Titan orbits Saturn four times in the time Hyperion orbits three times. This means Hyperion and Titan encounter each other at the same phase of Hyperion's inward and outward journey on its eccentric orbit so that the gravitational perturbations build up over time rather than averaging out. Orbital resonances play an important role in sculpting the architecture of the solar system, and there are many in play within the system of Saturn's moons and rings as well that produce a variety of interesting phenomena from Hyperion's rotation to waves in the rings and geysers on Enceladus.

4.7 Iapetus: the two-tone moon

Iapetus is the second-largest, after Rhea, of the mid-sized icy satellites of Saturn. Its orbit is much larger than that of the other regular satellites, however, and this is likely responsible for its distinctive appearance. In spite of its great distance from Saturn (59 R_S, where 1 R_S is the radius of Saturn, or about 60 300 km), Iapetus, like the inner moons, is tidally locked in synchronous rotation around Saturn[7]. Like the inner icy moons discussed above (but unlike the chaotically rotating Hyperion), Iapetus has a leading and trailing hemisphere. The combination of the synchronous rotation with Iapetus's large orbit gives rise to a unique and distinctive feature. The leading hemisphere of Iapetus is among the darkest surfaces in the solar system, reflecting just 5% of incident sunlight, while the trailing hemisphere is among the brightest in the solar system, reflecting 50% of incident sunlight (figure 4.13). For comparison, our Moon, on average, has an *albedo* (reflectivity) of about 14%.

One can imagine that the dark surface is the result of Iapetus plowing through some space dirt in its orbital journey around Saturn, its leading hemisphere getting coated with dirt like a car's windshield driven through a cloud of bugs. The trailing hemisphere, shielded from this polluting material, remains bright, pristine water ice. This relatively simple hypothesis poses many questions, and the answers are not so simple. What is the source of this dark material? Why is not coating the other moons of Saturn? Is there enough of it to explain the depth of the dark terrain (which can be measured by the appearance of small bright craters on the dark side)? How does the dark material wrap around to part of the trailing hemisphere, and why are the polar regions of Iapetus bright, even on the leading hemisphere?

The answers to some of these questions lie with yet another of Saturn's moons: Phoebe, the largest of the captured irregular satellites we learned about in chapter 3.

[7] The Earth's Moon orbits at an average distance of 60 R_{Earth} from the Earth, but Saturn is 9.5 times the size of the Earth, so while the relative separations are similar, Iapetus's orbit is about 9.3 times the size of our Moon's orbit.

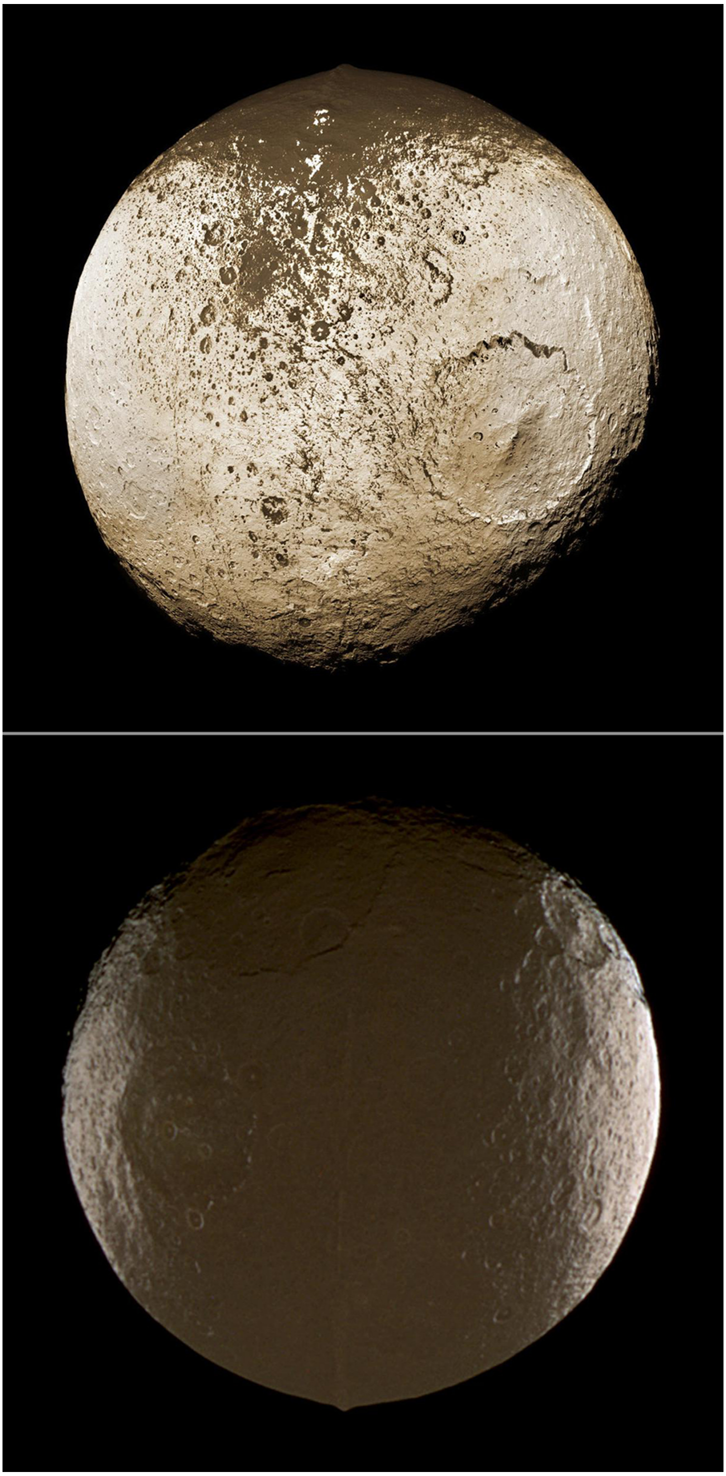

Figure 4.13. The two hemispheres of Iapetus have very different reflectivities. The leading hemisphere, on the left, is covered by a dark material, except near the poles, while the trailing hemisphere (right) is much brighter. Image Credit: NASA/JPL/SSI.

Phoebe is the source of what is, by sheer volume, the largest planetary ring in the solar system. This ring is so faint and so large that it escaped detection until 2009 when Anne Verbiscer at the University of Virginia and her colleagues used data from the NASA Spitzer Space Telescope to make a large mosaic of the region where they expected the ring to lie using the infrared region of the spectrum where the ring was expected to be relatively bright (figure 4.14) (Verbiscer *et al* 2009). It's difficult to see this ring with Cassini's instruments because it is an enormous faint cloud of dust, and Cassini is too close to it to be able to get the big picture that shows the slight contrast between the ring and empty space. It's difficult to get a good picture of a cloud if you are inside it, or even right next to it, especially if the cloud is so tenuous that it blocks only 2-millionths of one percent of the light passing through it. This ring is similar to the G ring in that it is made of dust particles knocked off of a moon by micrometeoroid impacts. In the case of the G ring, the tiny moon Aegeon is the source (chapter 3, figure 3.1), and the resulting ring is faint but also relatively small in extent. The Phoebe ring, on the other hand, is vertically (in the north–south direction) 20 times as large as Saturn itself, and extends well over 100 times the radius of Saturn from its inner edge to its outer edge. The dust from Phoebe fills such a large space because it is launched from Phoebe itself, and Phoebe is on a very eccentric (elliptical) and inclined (tilted) orbit around Saturn, with a mean distance from Saturn of almost 13 million km, more than 3.5 times the size of Iapetus's orbit. Cassini was only able to visit Phoebe once, during its initial approach to Saturn. As Phoebe orbits Saturn it makes large excursions north and south of Saturn's equatorial plane, and its distance from Saturn ranges from 11 to 15 million km.

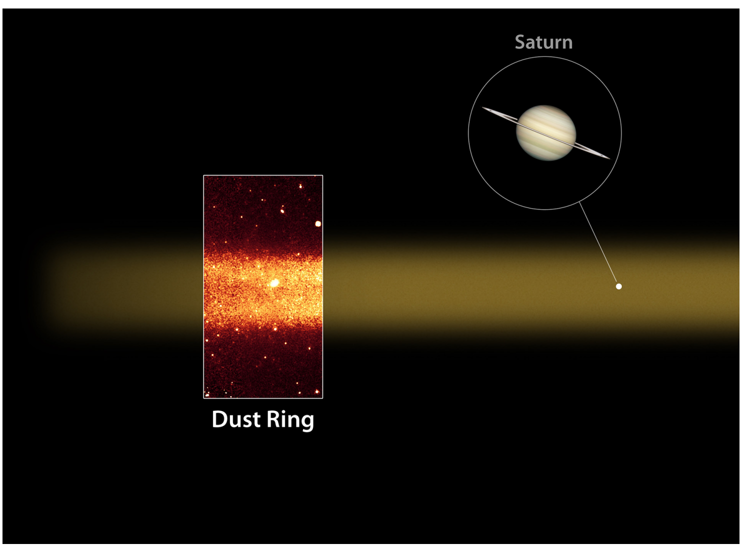

Figure 4.14. The faint, but enormous, dust ring produced by impacts onto the moon Phoebe was revealed in images taken by Anne Verbiscer and colleagues using the NASA Spitzer Space Telescope. The dot on the right indicates the size of Saturn and the main rings to scale with the dust ring which is too faint to observe without long exposures and careful image processing. Image Credit: NASA/JPL/Anne Verbiscer (Univ. Virginia).

All along the way, small particles are liberated from its surface by the faint but continuous bombardment of interplanetary micrometeoroids. Phoebe is large enough to provide a significant target area to these interplanetary impactors, but not so large that its gravity prevents the ejected dust particles from escaping the moon entirely. These particles occupy the space traversed by Phoebe in its orbital journey, and the smallest ones gradually spiral inwards toward Saturn due to the effects of the weak but persistent force of sunlight impinging on the particles.

Here is where Phoebe connects to Iapetus. Iapetus plows through the Phoebe ring particles as it orbits Saturn. Phoebe, and therefore the dust knocked off it to form the Phoebe ring, orbits Saturn in the retrograde direction, while Iapetus is a regular, prograde satellite. The Phoebe ring thus creates a steady rain, or hail, of dust particles onto the leading hemisphere of Iapetus, darkening its icy surface. The other, smaller outer irregular satellites also contribute small amounts to this inwardly migrating population of dust particles. An immediate test of whether this dust is what we see on the dark, leading hemisphere of Iapetus is to compare the spectral properties of the dark face of Iapetus with the spectrum of Phoebe[8], the source of most of the dust. It turns out that the spectrum of Phoebe is not a good match for the dark hemisphere of Iapetus. Furthermore, the sweepup of dust would lead to a gradual transition from the leading hemisphere to the trailing hemisphere: we would expect to see some terrain with an intermediate brightness between the dark face and the bright face. Instead, the transition shows a mottling of bright and dark areas, but nothing in between (figure 4.15). So although Iapetus sweeps up the dark material from Phoebe and the other outer moons, something else is going on to create the dramatic dark/bright asymmetry.

In 2010, John Spencer of the Southwest Research Institute in Boulder, Colorado, and colleagues published a paper that provides an explanation for the distribution of bright and dark terrain on Iapetus. Because Iapetus is in synchronous rotation with its orbit, but also on a very large orbit, both its orbital period and its day are long: 79.3 Earth days. This is the longest day of any Saturnian moon. Moons with orbits much larger than that of Iapetus do not rotate synchronously because they are too far from Saturn for tidal locking to take place. Iapetus's long day means the dayside has a long time to heat up, and the nightside has a long time to cool off, so there is a relatively large 40 K temperature difference between noon and midnight on Iapetus. The difference is only large in a relative sense, because the surface is still extremely cold by Earthly standards everywhere on Iapetus at all times[9]. If the dust from the Phoebe ring produces even a slight darkening of the leading hemisphere, then during daytime on that hemisphere it gets even warmer because it absorbs more sunlight. This increase in temperature and the long duration of the day is enough to increase the loss rate of water ice from the leading hemisphere due to *sublimation*[10]. The sublimated water

[8] The reflectance spectrum of an object is a measure of how much light is reflected by that object as a function of the wavelength of light. It is a powerful diagnostic of the composition of a material as well as physical properties such as porosity and the size of grains on the surface.
[9] 140 °C below zero on the 'warm' dayside.
[10] Sublimation is the process of evaporation from the solid phase to the vapor phase, such as when ice cubes are removed from the freezer and give off steam.

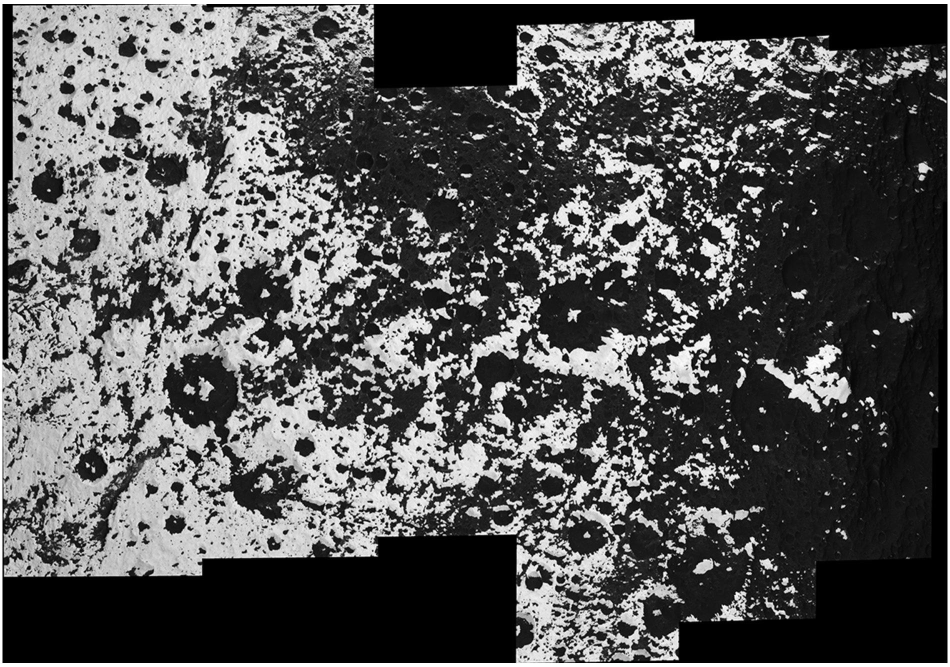

Figure 4.15. This 2007 mosaic of Cassini images of Iapetus was assembled by the Imaging Science team led by Carolyn Porco at the Space Science Institute in Boulder, Colorado. Bright and dark areas are intermixed at the transition between the dark hemisphere on the right and the bright hemisphere on the left, but there are no gray areas. In the transition region the floors of craters are darker than the crater walls. Bright peaks can be seen in the centers of some of the larger craters. Image Credit: NASA/JPL/SSI.

molecules do not escape Iapetus entirely, but instead land somewhere else on the surface. If that new location is warm (such as on the dark leading hemisphere) the water molecules are likely to hop off the surface again. They are likely to continue hopping until they land on a cooler surface, and surfaces without dark material reflect more sunlight and are therefore cooler. So water molecules preferentially migrate from the leading hemisphere, due to its initial coating of material from the Phoebe ring, to the cooler, trailing hemisphere. This leaves behind non-icy, dark material on the leading hemisphere, and provides a fresh, bright coating of water ice on the trailing hemisphere. The cold poles are also bright for the same reason.

The same process happens even on very small spatial scales. The bottoms of craters tend to get to higher temperatures than the top of a hill, for example, because the crater acts as a trap for heat. The temperature of a surface is determined by a balance between the energy flowing into the surface and the energy loss from the surface. Absorption of sunlight is a primary heating mechanism, and energy is lost through conduction into the interior, sublimation of ice, and thermal radiation. If the thermal radiation is prevented from escaping to space, whether through absorption by greenhouse gases in an atmosphere, as on Earth, Mars and Venus, or by physical barriers such as the walls of a crater, some heat is returned to the surface and the temperature rises. Indeed, in the transition region of Iapetus, crater floors are dark, while the peaks of mountains in the centers of those same craters are bright (figures 4.15 and 4.16). So the dark material on Iapetus is not primarily from the Phoebe dust ring, but it does owe its existence to the ring. A slight darkening of the leading hemisphere by Phoebe dust triggered a positive feedback loop where bright ice sublimated away from the leading hemisphere and coated the trailing hemisphere, making the leading hemisphere darker due to a lack of water ice, and the trailing hemisphere brighter due to an overabundance of it.

This phenomenon was first observed and explained on the icy moons of Jupiter which are much warmer than the moons of Saturn due to Jupiter's smaller distance from the Sun. Spencer did not expect the process would operate at Iapetus because water sublimation is so slow at the lower temperatures there. Only the very long day of Iapetus, allowing daytime temperatures to creep a bit higher, and the broad initial coating of the leading hemisphere by Phoebe ring dust, make the thermal segregation process work. The inner moons of Saturn are on smaller, faster orbits and therefore have shorter days which prevents their daysides from heating up as much as that of Iapetus.

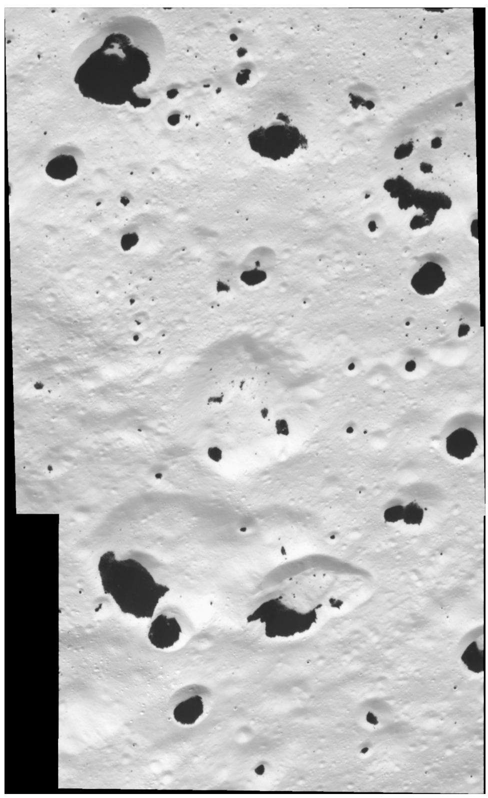

Figure 4.16. The bottoms of larger craters near the transition between the bright and dark hemispheres on Iapetus are as dark as the dark hemisphere because they reach higher temperatures in the daytime than flat terrain. These higher temperatures cause water ice to sublimate away, leaving behind dark, ice-free material. Image Credit: NASA/JPL/SSI.

The two-tone nature of Iapetus is not the only oddity of this moon. Its equator features a prominent ridge that gives the impression that the moon was assembled rather hastily by smashing the top half into the bottom half with a little too much force (figure 4.13). Unlike the leading–trailing asymmetry, which had been noticed by Giovanni Cassini in 1671 when he first discovered Iapetus, the ridge was only discovered in 2004 by the spacecraft bearing his name. The flanks of part of the ridge were observed by Voyager 2 in 1981 and dubbed the 'Voyager Mountains', but the full extent of the ridge was unknown because most of the ridge is in the dark terrain. Voyager did not have the sensitivity to make out the ridge in the dark terrain (figure 4.17). Cassini's cameras were able to obtain long exposures of the dark hemisphere, revealing the detail seen in figure 4.17 in spite of the low reflectivity of the surface. These long exposures were enabled by the sophisticated target-tracking capabilities of Cassini. The ridge is not continuous around the moon, lying primarily in the dark, leading hemisphere, but there are a number of tall (10 km), isolated mountains on the equator on the bright trailing hemisphere. The altitude of the ridge above the surrounding plains is about 20 km, making it taller than all but two other known mountains in the solar system: Olympus Mons on Mars at 21.9 km from base to peak, and the central peak of an enormous crater on the asteroid Ceres, also about 22 km high.

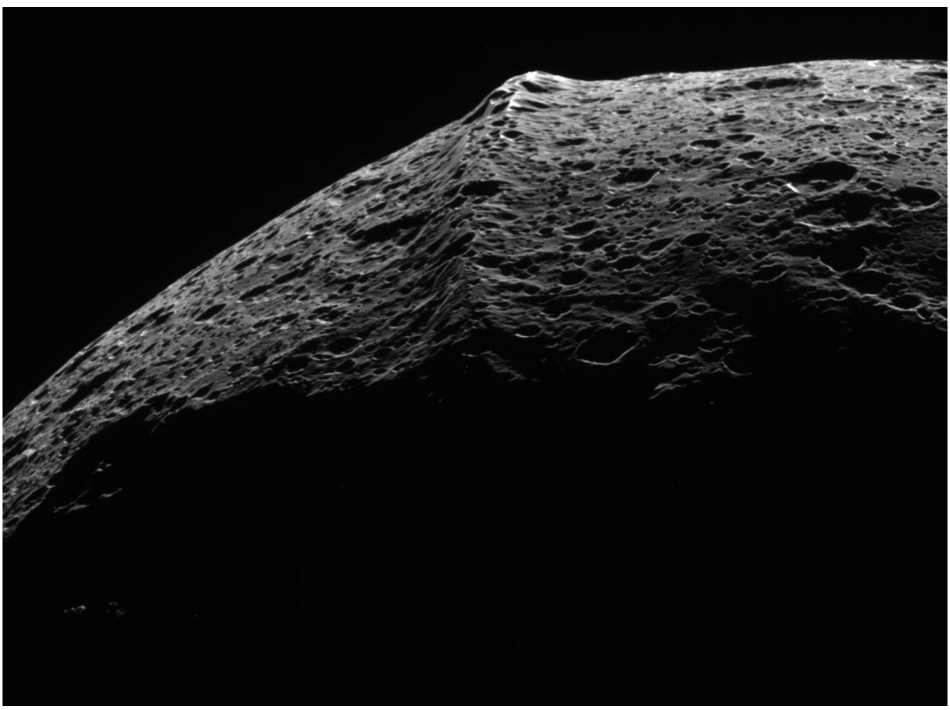

Figure 4.17. This view of the dark, leading hemisphere of Iapetus shows a portion of the 20 km high ridge that extends along its equator. Image Credit: NASA/JPL/SSI.

It is not unusual for moons and planets to have a larger equatorial radius than polar radius. Spinning objects, even those made of rock and ice, deform slightly into an oblate shape, with a shorter polar axis than the equatorial diameter. The faster the spin rate and the more deformable the planet, the larger is the *oblateness*. The Earth is 43 km larger across the equator than it is from pole to pole for this reason. Saturn, spinning much faster and a more deformable planet altogether, is a whopping 10% or 6000 km smaller along its rotational axis than across the equatorial plane. Iapetus shows signs of just such a spin-related flattening, but the equatorial ridge is a narrow feature above and beyond the moon's oblateness. The oblateness of Iapetus can be explained if the moon originally had a much faster rotation rate, a day perhaps as short as 16 h, causing the moon to flatten by about 4.6%. When moons and planets first form, they are warm due to the energy released from the kinetic energy of all the material that forms them coming together as well as energy released from radioactive materials naturally present in the solar system. Over time this energy is lost to space in the form of thermal radiation. When Iapetus first formed it would have been warmer and partially molten in its interior, allowing an initially rapid spin to deform it into an oblate (flattened) spheroid. As it cooled, it froze into this oblate state, so that as its rotation rate slowed due to tidal locking it retained its flattened profile.

In order to produce the ridge from an early, rapid rotation, Iapetus would have to have formed quickly and cooled quickly. This could have been the result of early heating from a radioactive isotope of aluminum that decays quickly, allowing the moon to freeze-in a prominent equatorial bulge while it was still rotating quickly. A problem with this scenario, though, is why Iapetus alone, of all the moons in the solar system, has such an equatorial ridge. Explaining its uniqueness in this regard requires invoking special circumstances for the formation of Iapetus, such as an impact that changes the rate of rotation more quickly than tidal de-spinning (Kuchta *et al* 2015, Levison *et al* 2011). An alternative explanation for the ridge relies on another unusual aspect of Iapetus: the large size of its orbit.

The strength of the force of gravity between two objects is inversely proportional to the square of the distance separating them, and proportional to the masses of the two objects. Moons orbit their respective planets rather than orbit the Sun because they are much closer to their planets than they are to the Sun. This proximity to the planet means the planet's gravity wins out over the Sun's gravity even though the Sun's mass is much greater than the planet's mass. Similarly, there is a region around a moon where its gravitational influence dominates the gravitational influence of the planet. The region around any object where its gravity is the dominant gravitational force is called the *Hill sphere*, named after 19th century American astronomer George William Hill. Large, massive objects have large Hill spheres, and objects that are relatively isolated also have large Hill spheres. Our Moon orbits safely within the Earth's Hill sphere. Were it about four times further from the Earth, however, it would be outside the Earth's Hill sphere, and the gravitational influence of the Sun would win out over that of the Earth, eventually causing the Moon to enter its own independent orbit around the Sun. The large masses of Saturn and the other giant planets together with their great distances from the Sun give them large Hill spheres and enable them to capture their collections of irregular satellites from interplanetary space.

By virtue of its great distance from Saturn and relatively large size for such a distant moon, Iapetus itself has a large Hill sphere. This means that there is a relatively large region of space around Iapetus in which it can harbor its own satellites, moons of a moon as it were, or indeed even a system of rings. If Iapetus were hit by another moon of Saturn or an interplanetary interloper, the resulting debris could have formed a ring around Iapetus. Forming as it did by an impact onto Iapetus, the spin of Iapetus would be set to the same direction as the orbiting debris from the impact: the ring would orbit above Iapetus's equator. But such a ring would be short-lived due to perturbations from the Sun and Saturn as well as interactions between the particles in the ring. Those hypothesized Iapetian ring particles would have rained down on the moon, piling up to form what we now see as a cratered equatorial ridge (Levison *et al* 2011).

Lending support to this hypothesis is the unusual density of craters on Iapetus. Its great distance from Saturn means that it should suffer fewer impacts, and impacts at lower speeds which produce smaller craters, than its sibling moons on smaller orbits. In reality it has more large impact basins than the inner moons, an observation that is difficult to reconcile with a population of impactors from outside the Saturn system (asteroids and comets). The clustering of irregular satellites into groups of small moons sharing similar orbits argues for an evolving population of moons, growing when Saturn captures an interplanetary interloper or when an interloper hits and shatters a moon. Iapetus, with its combination of a large orbit and large size, is uniquely positioned in the Saturn system to capture some of this debris within its Hill sphere and eventually have its surface battered by the infalling material.

We noted above that the dark material on Iapetus has a different spectrum than Phoebe, indicating that while the Phoebe ring dust may have triggered the sublimation and condensation transport of ice from the leading hemisphere to the trailing hemisphere, the dark material itself is not predominantly from Phoebe. Other spectral measurements of the moons and rings suggest that the dark material, seen also on the other moons, comes from outside the Saturn system. The source may be those same captured comets that produced a ring around Iapetus before eventually falling onto the surface, and, to a lesser extent, bombarded the other inner moons. The top 30–50 cm of material on Iapetus's dark side may be a collection of carbon-rich cometary gunk that formed much further from the Sun. It has now been conveniently collected on Iapetus for some future mission of exploration to collect and analyze to help us complete the history of our solar system.

4.8 Enceladus: Saturn's old faithful

The first unambiguous evidence that something was happening at Enceladus came from Cassini's magnetometer, an instrument that measures the strength and direction of the magnetic field as Cassini flies through it. When Cassini flew by Enceladus for the first time in February 2005 it measured a large deflection in

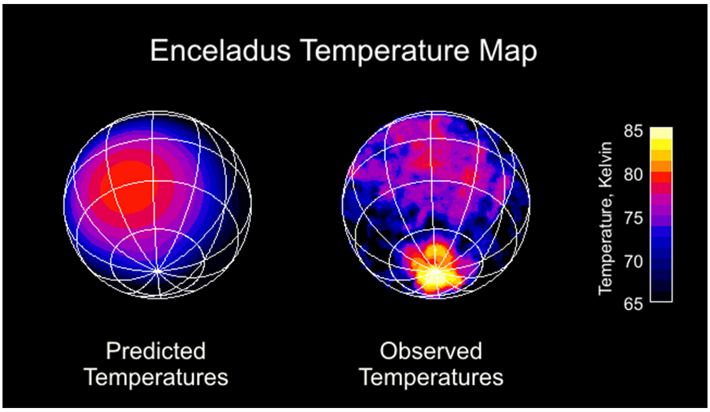

Figure 4.18. This temperature map of Enceladus shows a warm region at the moon's south pole. The expected warm spot corresponds to the point with the Sun most directly overhead. While the temperatures are still quite cold, higher resolution images by the CIRS instrument show that the hot regions are confined to narrow 'tiger stripe' fissures crossing the south pole. Image Credit: NASA/JPL/GSFC.

Saturn's magnetic field. The suggested explanation by Michele Dougherty and colleagues on the magnetometer team was that there was an extended atmosphere of some kind near Enceladus (Dougherty *et al* 2006). The discovery was compelling enough to motivate the project managers to approve a change to Cassini's trajectory to bring the next flyby of Enceladus, only a few months later, much closer (166 km instead of 1000 km) to its surface[11]. That next flyby, in July 2005, confirmed that water vapor is erupting from the south polar region of Enceladus, making it the first and only known geologically active icy body in the solar system.

The discovery of Enceladus's geysers is a perfect example of the value of having multiple instruments studying a complex system. It is like the ancient Indian parable of the blind men encountering an elephant: each one comes to a different conclusion based on the part of the animal he touches. The Cassini magnetometer could tell that there was some sort of electrically conducting 'barrier' to Saturn's magnetic field in the vicinity of Enceladus and larger than the moon. An atmosphere of water vapor would be consistent with this measurement. The Composite Infrared Spectrometer (CIRS) measured temperatures on Enceladus and found that four fissures crossing the south polar terrain were much warmer than the surrounding terrain, and too warm to explain from solar heating (figure 4.18) (Spencer *et al* 2005). The Ultraviolet Imaging Spectrograph (UVIS) observed the spectrum of a star as it passed behind the south polar region of Enceladus in a stellar occultation. The starlight dimmed near the south pole, and the spectrum of the light that got through to UVIS matched laboratory spectra of water vapor (Hansen *et al* 2005). The Ion and Neutral Mass Spectrometer (INMS) directly sampled water molecule products as it flew by Cassini (Waite *et al* 2005). The Cosmic Dust Analyzer

[11] Trajectory changes are not easy to make. Cassini is almost always on a ballistic (meaning no rocket propulsion being used) trajectory, falling around Saturn from one satellite encounter to another. It required Herculean efforts by the project to design, test and implement this trajectory change on such short notice.

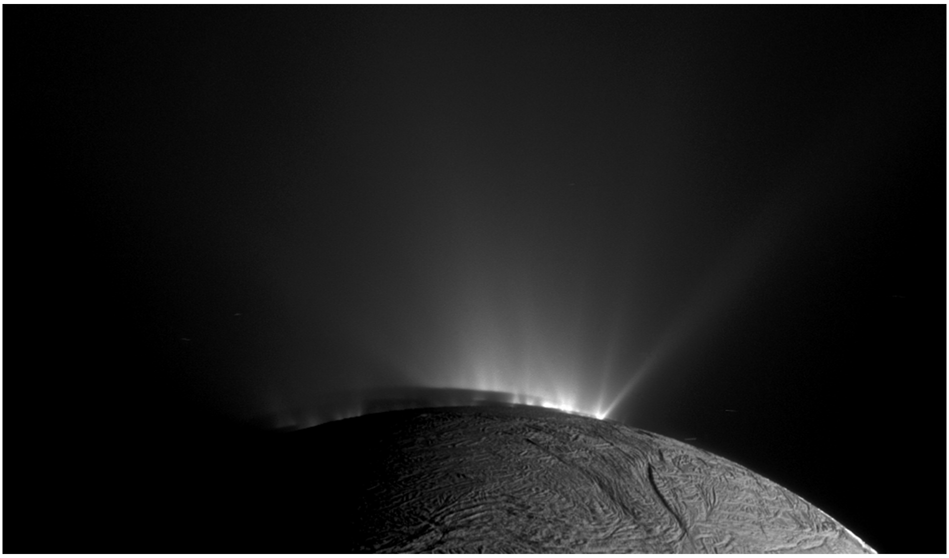

Figure 4.19. Cassini's cameras capture the geysers of water vapor and ice crystals erupting from the 'tiger stripe' fissures that cross the south pole of Enceladus. This image demonstrates the discrete sources for the geysers. The shadow of the moon partially blocks the lower portion of the jets from the more distant fissures over the horizon. Image Credit: NASA/JPL/SSI.

(CDA) detected enhanced numbers of microscopic solid particles hitting it during the flyby (Spahn *et al* 2005). Finally, Cassini images revealed the active geysers themselves (e.g. figure 4.19) (Porco *et al* 2005).

Something is heating the interior of Enceladus enough to boil water vapor off into space through fissures over the south pole. Based on the amount of water vapor being produced, determined from the UVIS stellar occultation measurements, the speed of the vapor, determined from images and occultations, and measurements of Enceladus's gravity, the source of the geysers must be liquid water beneath the south pole. Precise measurements of how Enceladus rotates as it orbits Saturn show that the wobble of the surface due to changing tidal forces (figure 4.5) is too large if the moon were solid from surface to core. Instead, the surface must be decoupled from the interior by a global subsurface ocean of liquid water. Models indicate that the ocean is a few tens of kilometers in depth, and that it is buried beneath an ice shell of variable thickness, ranging from perhaps just one or two kilometers at the south pole to 20–30 km at the equator, and perhaps 10 km at the north pole (Iess *et al* 2014, Hemingway 2016).

This ocean is the source of the geysers, but it raises a lot of questions for the history of Enceladus. It is difficult to maintain such an ocean in equilibrium with the ice above it without a large source of energy. The uneven ice surface above the ocean should flow laterally to reach a uniform thickness. The water in the ocean may either be freezing out onto this ice shell ceiling, or the ice shell might be melting into the ocean. Another question is why there are geysers only at the south pole. A commonly invoked but not entirely satisfying explanation is that an impactor punched through the ice shell in the past, resulting in a local thinning (Roberts *et al* 2016).

But if the liquid water is in a global subsurface ocean, why are the geysers only at the south pole? The active zone is centered quite precisely on Enceladus's south pole. And why is Enceladus active at all, of all of Saturn's moons? The answers to both questions are at least partly due to tidal interactions with Saturn. If there is a warm blob somewhere inside Enceladus, it would be extremely unlikely for it to be perfectly centered, or perfectly uniformly distributed, in the moon's interior. Wherever random chance places it, it causes material to expand and rise toward the surface, in much the same way that there are volcanic upwellings on the Earth. If there was a large impact that thinned the ice shell at one location, this also affects the mass distribution of the moon. This gives it an oblong distribution of mass even while the outer shape remains essentially spherical. Once it has that oblong distribution, tidal flexing of the moon will cause the moon to tip over until the low-density blob is on its rotation axis, meaning the thin part of the ice shell will end up at either the north or south pole (Nimmo and Pappalardo 2006). A flip of the coin, or moon in this case, placed Enceladus's hot spot at the south pole (figure 4.20). The recent results showing that the subsurface ocean is global means that the south pole only appears hotter because the subsurface water is close enough to the surface that it can erupt as geysers, carrying the heat of the warm water with it. The water beneath the north pole, and the rest of Enceladus, is at a comparable temperature, but the heat it gives to the thicker overlying ice shell is not enough to significantly raise the temperature of the surface of the moon that we observe.

But what provides the energy to maintain a large subsurface ocean on a tiny moon of Saturn? There is one other highly active moon in the solar system: the innermost Galilean satellite of Jupiter, Io. Io's surface is free of craters due to continuous eruptions from sulfur volcanoes. The heat source for Io's volcanoes is *tidal flexing*. Before a moon settles into synchronous rotation, tidal stretching of the moon continually changes its shape as the long dimension points at the planet, and the moon's rotation causes different pieces of real estate to move onto the long dimension. It takes energy to stretch a moon this way, and that energy comes from the rotation of the moon until it settles into synchronous rotation (figure 4.5). In the case of Io, it keeps flexing even though it is in synchronous rotation because its orbit is perturbed in a regular fashion by the neighboring moons Europa and Ganymede. Io orbits Jupiter exactly twice for each orbit of Europa, and Europa orbits Jupiter exactly twice for each orbit of Ganymede. These strong orbital resonances mean that Io is pulled onto an eccentric (non-circular) orbit by the gravity of the other moons, and this results in a changing amount of tidal stretching of the moon as its distance to Jupiter varies over the course of an orbit. It is amazing that what may seem like a small perturbation can have such dramatic consequences, but the existence of volcanic activity on Io was famously predicted by Stan Peale, Pat Cassen and R T Reynolds in a paper published just months before volcanoes were discovered by Voyager 1 (Peale *et al* 1979). They calculated that the heat generated by the tidal flexing due to its slightly eccentric orbit would be great enough to power volcanic activity.

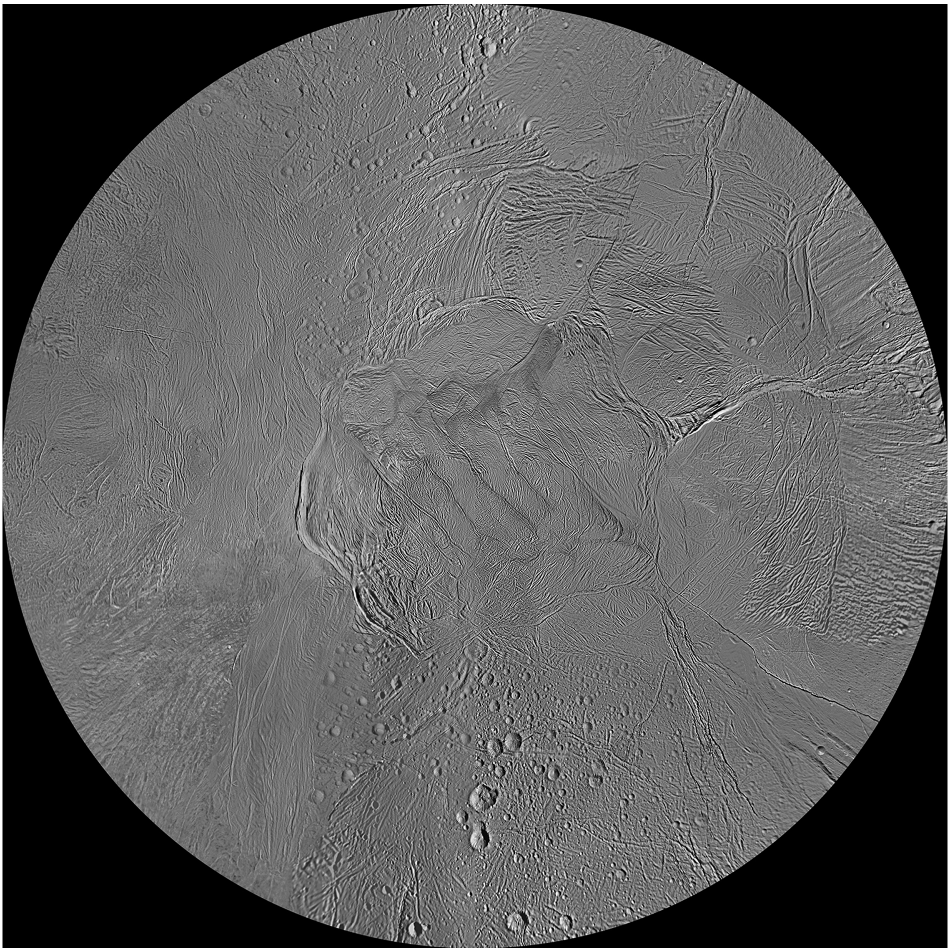

Figure 4.20. This mosaic of Cassini images is centered on Enceladus's south pole, marked by four prominent fissures nicknamed 'tiger stripes'. The geysers emanate from these fissures. Surrounding the south pole is a complex pattern of fractures produced by tidal stresses and the upward pressure of the warm water beneath the south pole. Image Credit: NASA/JPL/SSI.

If Io is a textbook case for tidal heating, Enceladus is anything but. Although Enceladus is in a 2:1 resonance with Dione (it orbits Saturn twice for each of Dione's orbits), it is not clear that this can provide the amount of heat observed flowing from Enceladus's south pole. Worse, the energy required to maintain a global ocean is much greater even than what is inferred from the high temperatures we see at the south pole. Heating from the decay of any radioactive material present in Enceladus is almost certainly much weaker than tidal heating due to Enceladus's small size and correspondingly small reservoir of radioactive materials, so tidal flexing remains the favored mechanism. Also, the activity of the geysers seems to vary with Enceladus's position in its orbit, increasing and decreasing with the small changes in the moon's distance from Saturn consistent with the predictions of tidal flexing controlling the amount of gas production (Hedman *et al* 2013). However, the tides affect not just the amount of heat, but also the configuration of the cracks at the south pole which get pulled and stretched over the course of an orbit. The water vapor blasting through these cracks may have larger or smaller paths to escape to open space as the fissures flex over the course of an orbit.

One difficulty is that the amount of power generated by tidal flexing depends on the physical properties of the interior of the body being flexed. It turns out that if Enceladus already has a global ocean in its interior then tidal flexing may be able to generate enough power to keep the ocean liquid. But if you start with a solid interior, tidal flexing, at least at the current rate, is insufficient to melt the ice to produce the ocean. Furthermore, the current value of the eccentricity of Enceladus does not seem to be in equilibrium with the perturbations from Dione and the dissipation of energy from the south pole. The full story of the origin of Enceladus's ocean, how old it is, whether it is freezing out or not, and what source of energy maintains it, is still being discovered and may require observations from future missions dedicated to studying this intriguing moon.

The presence of liquid water is a bellwether for habitable environments. Liquids enable much more rapid mixing of chemicals and more rapid chemical reactions necessary for life. It is far from the only ingredient necessary, of course. The other raw ingredients for life: heavier elements and more complex molecules, energy to drive chemical reactions, and physical mechanisms to confine and concentrate molecules are also necessary. Some of these other ingredients are present at least at some level at Enceladus. Measurements of the composition of dust and gas in the plumes by Cassini have indicated the presence of some complex carbon-bearing molecules (Postberg *et al* 2017) indicating that some chemical reactions are taking place in the ocean. There are very few environments in our solar system that are even potentially habitable, and we now know that this tiny moon of Saturn is one of them.

The geysers have consequences far beyond Enceladus itself. The water vapor carries small amounts of silicate particles along with it from Enceladus's rocky core and condenses into grains of solid ice after it leaves the fissures. Much of this material reimpacts Enceladus, coating the south polar region like a fresh snowfall. The southern hemisphere is also tectonically deformed by the upward pressure of the warm water, causing a network of fractures. The southern hemisphere as a consequence is completely free of craters, while the northern hemisphere has a more conventional cratered surface (figure 4.21). But much of the material escapes Enceladus's gravity and goes into independent orbits around Saturn, forming its tenuous E ring. As is the case with the material in the Phoebe dust ring, the E ring particles impact the neighboring icy moons of Saturn, as well as the main rings.

Clearly Enceladus has had a complicated history that involved episodes of greater heating in the past. It is possible that its ocean is a remnant from strong radiogenic heating shortly after its formation, but higher eccentricities in the past would likely be necessary to maintain the liquid ocean over the age of the solar system. Such high eccentricities could be produced as the moons' orbits tidally evolve and they pass into and out of resonances with each other. Mimas ended up on a very different evolutionary path from its neighbor perhaps due to subtle differences in orbital

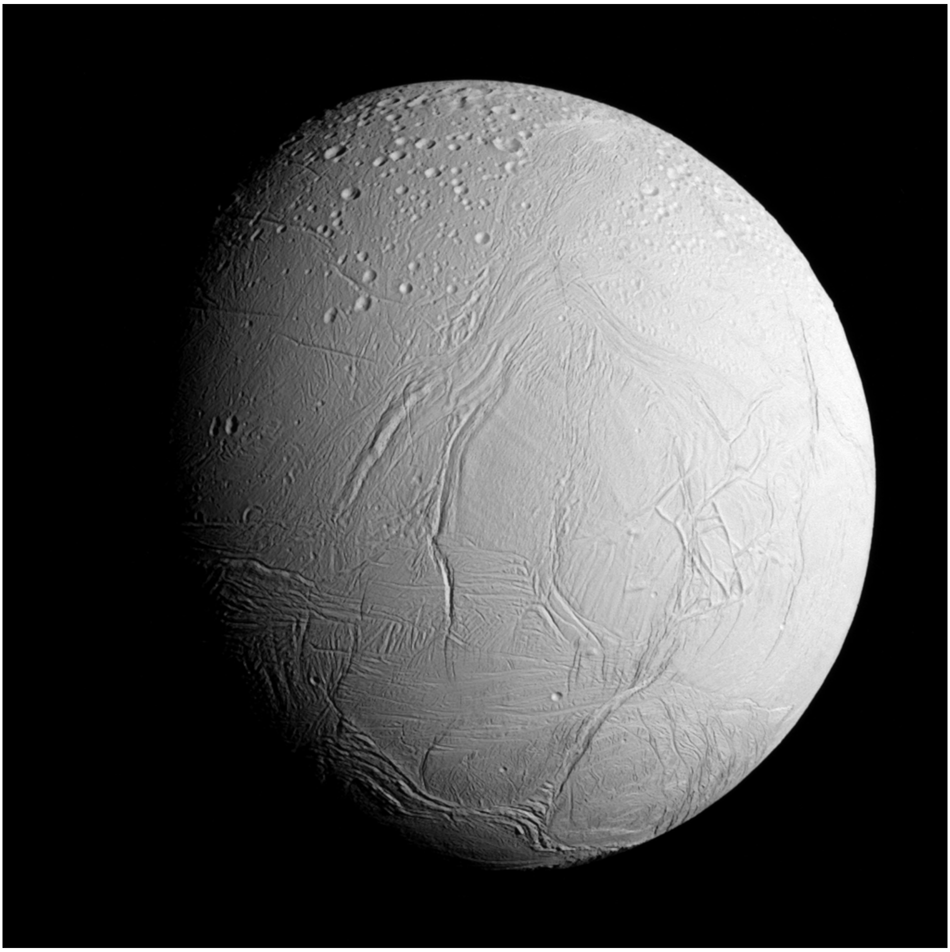

Figure 4.21. This global view of Enceladus shows the dichotomy between the southern hemisphere, which is almost entirely free of impact craters, and the more heavily cratered northern hemisphere. Upwelling of ice near the south pole as well as fallout of icy grains from the geysers resurfaces the southern hemisphere, quickly destroying or covering up craters. Image Credit: NASA/JPL/SSI.

evolution that prevented it from ever getting hot enough to create or maintain a liquid ocean. We may not be able to determine a unique answer for the history of Enceladus, but we have learned from Cassini that it is a potential abode for life. Its history is intertwined with the other moons through resonances, and with Saturn's mighty ring system as we will see in the next chapter.

Further reading

The review chapters by Dones (Icy Satellites of Saturn: Impact Cratering and Age Determination p 613), Jaumann (Icy Satellites: Geological Evolution and Surface Processes p 637) and Spencer (Enceladus: An Active Cryovolcanic Satellite p 683) in

Dougherty *et al* (2009), include discussions of many of the processes discussed in this chapter as well as references to prior works pre-dating Cassini.

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Chapter 5

Dynamic rings

5.1 Introduction

While the moons of Saturn are graced with poetic names from Greek mythology (and other mythologies once the number of satellites proliferated), its glorious rings are stuck with the letters A, B and C. Perhaps it was ignorance about what the rings actually are that led early astronomers to be hesitant to fix them with a more noble and definitive name such as Titan or Tethys. Designating a set of things by letters from the alphabet smacks of uncertainty and impermanence. And we must admit a considerable degree of uncertainty remains about some of the fundamental questions of Saturn's rings: how did they form? How old are they? How long will they last? What did they look like 1, 10 or 100 million years ago? What will they look like 10 million years from now? Was Saturn merely lucky to win the planetary rings jackpot, or is there something about its place in the solar system that makes it the best place for a broad, massive set of rings to set up shop?

Prior to the Voyager flybys of the early 1980s it was thought the rings were the remnant debris from the formation of Saturn and a relatively quiescent and perhaps uninteresting system, evolving slowly over the eons. The Voyagers showed a wealth of structure within the ring system that immediately upended this view. A handful of broad rings that could be counted (or lettered, in this case) on one hand, now came into focus as a myriad of structures as small as the Voyager cameras could see. These newly discovered waves, ringlets, and other narrow features, and the rings' nearly pristine icy composition, suggested a recent origin and changes happening on timescales of years, not millenia, let alone millions or billions of years. Untangling these mysteries has been one of the primary goals of the Cassini mission. (Results on Saturn's rings from the initial phase of Cassini's mission together with technical discussions and references for the processes discussed in this chapter are reviewed in the five ring chapters in Dougherty *et al* (2009).)

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5.2 The main rings

Before we tackle these questions and the phenomena that shape the rings, let's take a tour of the system. Figure 5.1 provides an overview of the ring system with a view similar to what one would get from a terrestrial telescope with the exception of Saturn's prominent shadow cast across the rings. From our Earthly vantage point, the Sun is shining on Saturn from almost the same direction as our line of sight, so most of the shadow of the planet on the rings would be behind the planet.

Figure 5.2 illustrates the regions of the main rings. The Cassini Division between the A and B rings resembles the C ring in color and density of material. The broad B

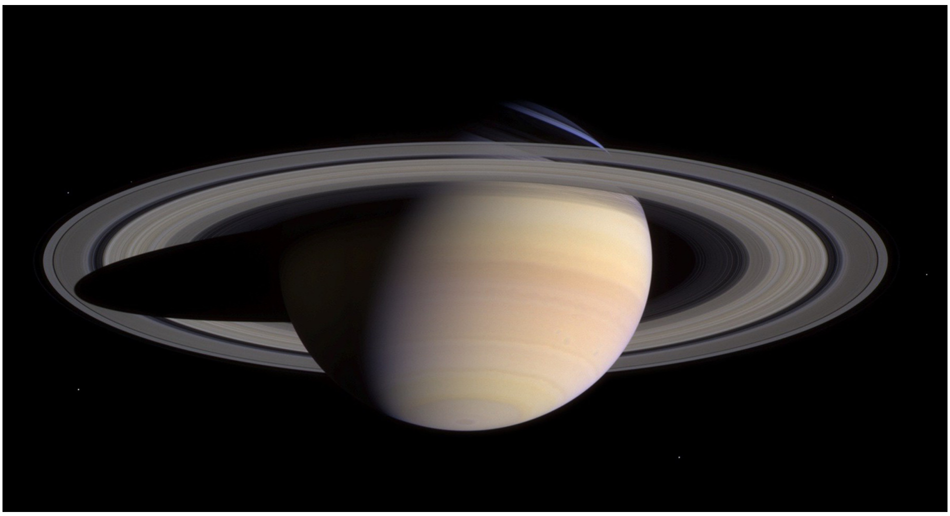

Figure 5.1. Saturn and its rings and a few small moons are seen in this image taken by Cassini shortly prior to its Saturn Orbit Insertion (SOI) maneuver in which it fired its main engine to lose enough energy to be captured by Saturn's gravity. Image Credit: NASA/JPL/SSI.

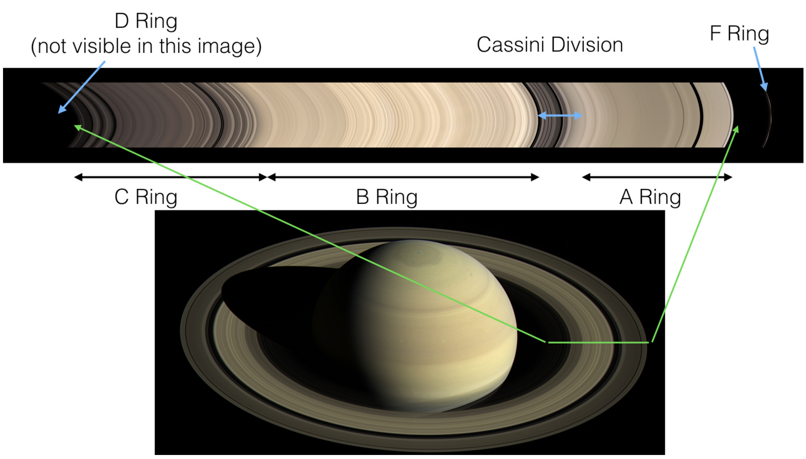

Figure 5.2. These images show the 'main rings' (A, B, C and Cassini Division) and the F ring. The faint D ring lies interior to the C ring and is not visible in the geometry and lighting of these images. Images: NASA/JPL/SSI.

ring is the brightest in reflected sunlight, and it is opaque in some areas. We know from how they reflect, absorb and scatter sunlight that the particles are composed mostly of water ice, and their collective behavior suggests that their densities are more like dense snowballs than solid ice. For a cloud of countless particles such as the rings, a useful measure to describe them is their transparency, measured as a percentage of light incident on the rings that makes it through to the other side. Figure 5.3 shows the transparency of the rings from an observation of a bright star (Beta Centaurii or Hadar) as the rings passed in front of it from the point of view of Cassini. The main ring regions seen in the images can also be identified in this plot, but we also see that there is a wealth of structure in each ring region. Occultation measurements of this type can be made with radio transmissions from Cassini to the Earth at different radio frequencies, and the rings are more or less transparent to different frequencies depending on how large or small the ring particles are. From these measurements we know that the particles in the main rings range in size from about one centimeter to several meters, though determining the size of the largest particles is complicated by their tendency to clump together.

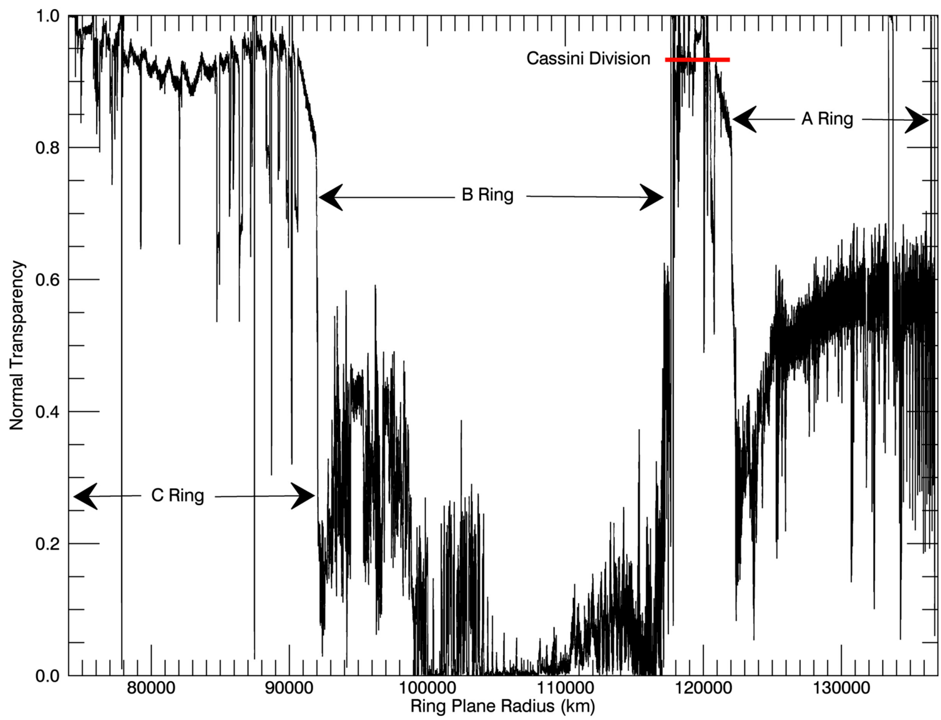

Figure 5.3. This figure shows the normal transparency of the rings from a stellar occultation observed by Cassini's Ultraviolet Imaging Spectrograph, where in this context 'normal' means it is the transparency that would be measured from a line of sight perpendicular to the plane of the rings. The curve goes to 1 at gaps in the rings and dips to 0 in the opaque central region of the B ring.

In chapter 3 we saw that the rings owe their existence to the tidal force exerted on the ring particles by nearby Saturn: while the weak gravity of the particles tries to assemble them into larger objects, they race around Saturn at different rates and are thus torn away from each other by Saturn's gravity. This tidal force is very strongly dependent on distance from Saturn, and beyond the Roche limit discussed in chapter 3, particles are able to stick together. The Roche limit itself, however, is not a singular boundary. For example, inside the Roche limit it is

Figure 5.4. The ringmoons Atlas (left) and Pan (right) have a distinctive flying saucer appearance due to accretion of a mantle of small particles around their equators. They have accreted debris from the rings to fill their Hill spheres. It is difficult to get a high resolution image of Pan because it orbits within the rings, making it impossible for Cassini to get very close, and difficult to get an image that does not have the rings partially obstructing the moon (far right). Image Credit: NASA/JPL/SSI.

Figure 5.5. This stunning view of Prometheus, which orbits between the F and A rings, shows its potato shape in the dim illumination of Saturnshine from the left. The surface has a softened appearance due to accretion of material from the F ring which covers and fills in craters. The image resolution is 200 m pixel^{-1}. Image Credit: NASA/JPL/SSI.

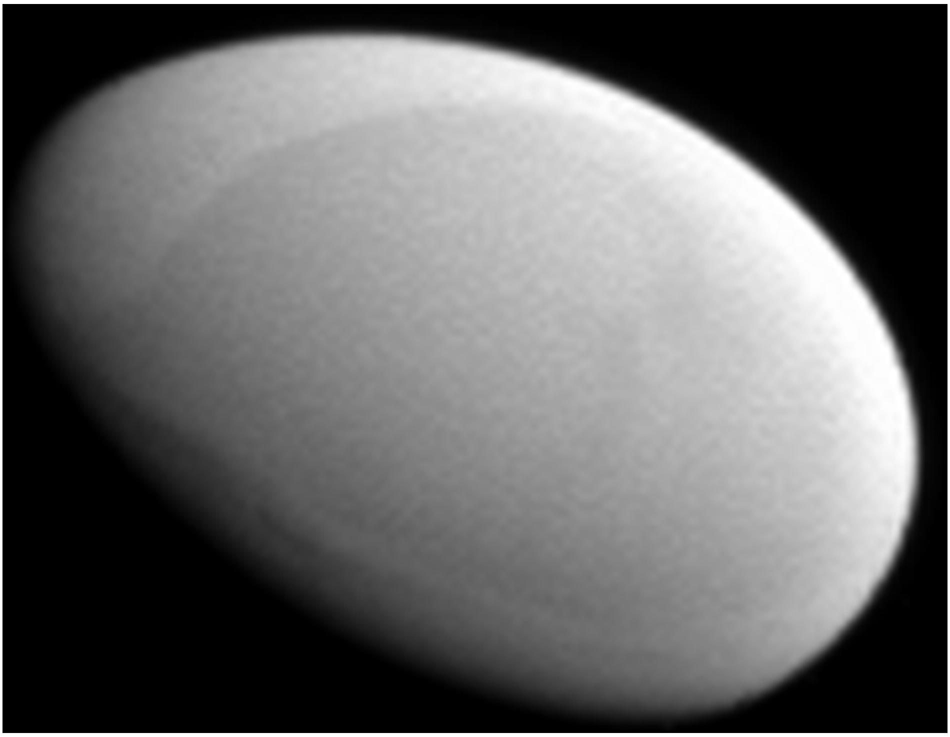

Figure 5.6. It is difficult to believe that this is a moon from its apparently perfectly smooth, egglike appearance. Like Prometheus and the other small, inner moons, Methone accretes material from the nearby rings, but its small size means that it quickly fills its Hill sphere which has an oblong shape this close to Saturn. Methone is only 3 km across. The resolution of this image is 27 m pixel^{-1}. No craters can be seen at this resolution, indicating that the moon has accreted material to cover up any impact scars. Image Credit: NASA/JPL/SSI.

possible for a small particle to gravitationally stick to a larger ring particle, while two similarly-sized particles might be torn apart by tides. This is because a ring particle, like a moon or planet, has its own tiny gravitational sphere of influence, or Hill sphere. The closer the ring particle is to Saturn, the smaller is its Hill sphere. At the Roche limit, the Hill sphere is larger than the particle, but not large enough to fit another comparably sized particle inside it. A small particle, however, can squeeze within the Hill sphere of the larger particle. At a certain distance from Saturn, well inside its Roche limit, the size of a ring particle's Hill sphere shrinks to become smaller than the ring particle itself. There, Saturn's tidal force is too strong to allow even a pebble to rest on the surface of a larger ring particle. Down, on such a ring particle, is toward Saturn, not toward the particle. The location of this point depends on the densities of the particles, but it's well within Saturn's main rings. The A ring, particularly near its outer edge, however, is close enough to Saturn's Roche limit to allow some particles to gravitationally stick together.

This limited accretion in the outer rings shapes, quite literally, the nearby moons (sometimes called ringmoons) and the rings themselves. In spite of its name, the Hill sphere is not spherical. For objects that are very close to Saturn, the Hill sphere is flattened: particles are pulled by Saturn's gravity off the north or south poles of a moon more readily than off the equator. This can be seen quite dramatically with the saucer-shaped moons Atlas, which orbits just outside the A ring edge, and Pan, which orbits within the A ring itself (figure 5.4). Further from Saturn the Hill sphere of a moon becomes less flattened (figures 5.5 and 5.6) and the accretion of material onto the moon takes on a more egglike shape, until, even further from the planet, the Hill sphere becomes much larger than the moon in all dimensions and does not affect its shape at all.

5.3 Self-gravity wakes

Within the A ring itself, ring particles continually collide with each other, but at a snail's pace[1]. The reason the collisions are so gentle is that the particles have been colliding with each other for so long. In the main rings a particle collides with a neighbor several times per orbit, and the orbits are only about 10 h long. These collisions are inelastic, meaning that some of the mechanical energy of motion of the particles is lost by conversion to heat or crushing of the surface. Quite rapidly, the relative motion between the particles damps down to a minimum. That minimum collision speed is set by two things: the gravitational stirring of the ring particles themselves, and the small relative velocity due to particles being on slightly different orbits around Saturn.

To see how small these collision speeds are, let's consider a relatively large ring particle with a radius of 1 m. Individual ring particles may be as much as 10 times larger than this in some ring regions, though as we will see below, even defining what is meant by 'individual ring particle' is not as straightforward as one might imagine. Two such particles on neighboring orbits separated by 2 m will have a grazing collision as the inner particle, with its slightly faster orbital speed, laps the outer particle. Since the orbital speeds are precisely calculable from Kepler's laws and the mass of Saturn, we can calculate the speed that the inner particle passes by, or nudges, the outer particle. This speed varies a bit from the inner edge of the rings to the outer edge, but at the center of the ring system at an orbital radius of 110 000 km, the collision speed due to this *Kepler shear* would be 0.2 mm per second (that's moving about twice the thickness of a human hair each second). The gravity of the ring particles also provides some small collision velocity. If we imagine our two ring particles are alone in the Universe, without the complicating effect of nearby Saturn, the gravitational interaction between the two particles would make them fall toward each other until they hit at a speed known as their escape velocity. For our 1 m ring particle made of porous ice, this is about 6 mm per second. The competition between the particles falling toward each other due to their mutual gravitational attraction and the particles falling away from each other due to the difference in the

[1] This is literally true. Although species of snail have a range of speeds, they actually overlap quite neatly with the range of collision speeds in unperturbed regions of Saturn's rings. In areas where the ring particles are stirred up for one reason or another, collision speeds may be almost as fast as a walking tortoise's pace.

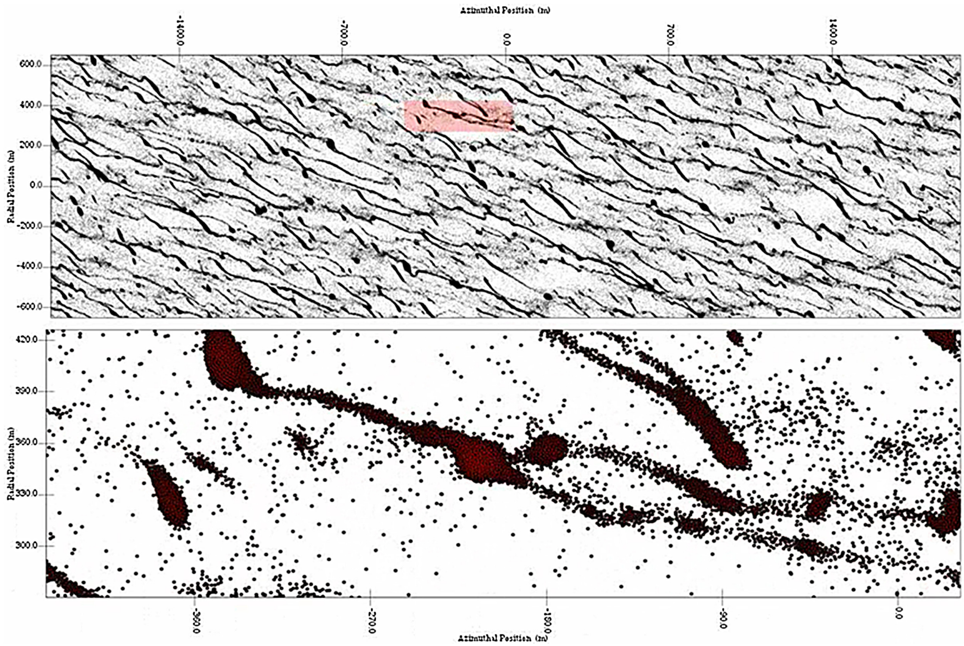

Figure 5.7. This computer simulation of particles in Saturn's rings shows the formation of ephemeral clumps called self-gravity wakes. Particles are orbiting left to right, and Saturn is down in this view. The lower panel is a zoomed-in view of the highlighted region in the upper panel. The simulation is of a very small patch of the rings. Particles closer to Saturn (at the bottom of the simulation) orbit Saturn faster and so move ahead of (to the right) the slower particles further from Saturn (at the top of the simulation). Collisions and gravity between the particles cause them to form clumps, but the orbital shear stretches the clumps out. Simulation courtesy of Mark C. Lewis, Trinity University.

gravitational force they feel from Saturn (the tidal force) can produce ephemeral clumps of particles dubbed *self-gravity wakes*[2].

A group of particles left to their own devices in space will form a spherical clump, but in orbit around Saturn the particles closer to Saturn orbit more quickly, so the clump gets sheared out into an elongated clump that is canted by about 25° from the direction of orbital motion. Computer simulations of the rings, where the motions and interactions of millions of individual ring particles are calculated, show the formation and evolution of these self-gravity wakes (figure 5.7) (Salo 1995, Lewis and Stewart 2009). Because these clumps are elongated and have a characteristic orientation determined by how quickly the gravitational force changes with distance from Saturn, they affect the appearance of the rings from different viewing geometries. You can see this effect by holding your hand, fingers spread, in front of you, with your fingers pointing away from you and up at a 45° angle. You can easily

[2] This is a terrible name because they are not 'wakes' at all, and, worse, there actually *are* things in the rings that truly are wakes, as we will see later in the chapter. I have done research on these structures and managed to get the name changed to the terrible 'self-gravity wakes' from the slightly more terrible 'gravitational wakes' that prevailed in the literature prior to Cassini.

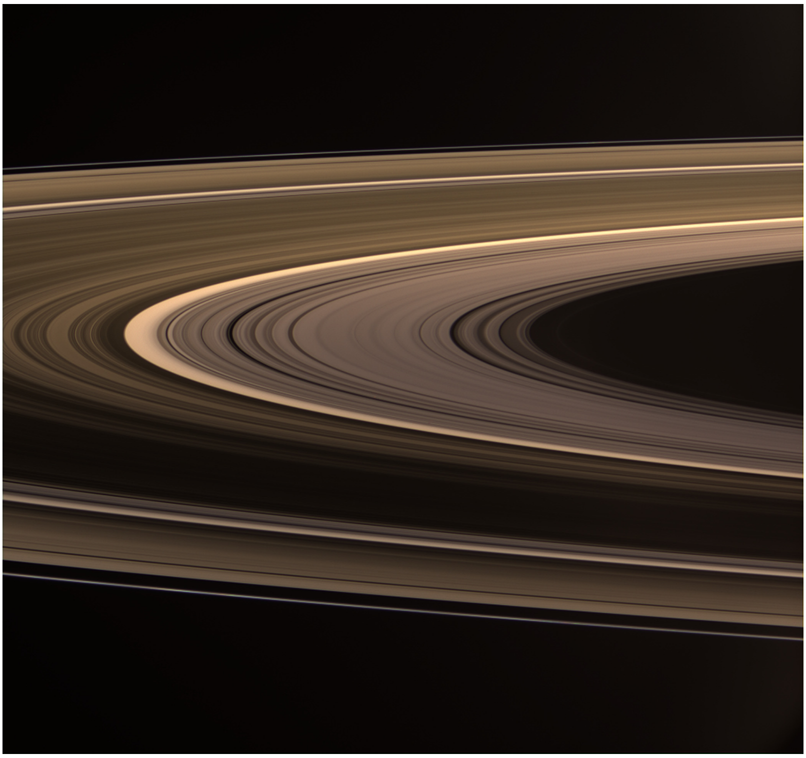

Figure 5.8. This view of the main rings was taken by Cassini from only 5° above the ring plane. From this geometry the effect of self-gravity wakes is quite apparent: the rings on the far side of the planet in this view are much brighter than those on the near side. This is due to the different orientation of the elongated self-gravity wakes with respect to the Sun and Cassini with longitude around the rings. Image credit: NASA/JPL/SSI.

see past your fingers through the spaces in between them. If you now rotate your hand left or right, your fingers block the spaces in between them from your view. Your hand has become more opaque from the vantage point of your eyes. And so it is with the rings (figure 5.8).

Although Cassini's cameras cannot resolve individual self-gravity wakes, the Ultraviolet Imaging Spectrograph (UVIS) has a detector that can measure the brightness of a star 1000 times each second as the rings pass in front of, or occult, the star (figures 5.3 and 5.9). Typical speeds of the rings in front of the star as seen from Cassini are about 10 km s^{-1}, meaning that UVIS makes measurements of the transparency of the rings with a resolution of about 10 m. These occultations provide one-dimensional slices of the rings at this high resolution, but they are affected by smear due to the orbital motion of the ring particles themselves which is generally much faster than the motion of the footprint of the star on the rings. We were able to find some stars that passed behind the rings in such a way that the stellar spot moved slowly relative to the ring particles at certain locations. These 'particle tracking occultations' provide us with direct measurements of the self-gravity wakes whose collective effects have been seen in numerous observations, such as in figure 5.8, but are too small to see individually (figure 5.10).

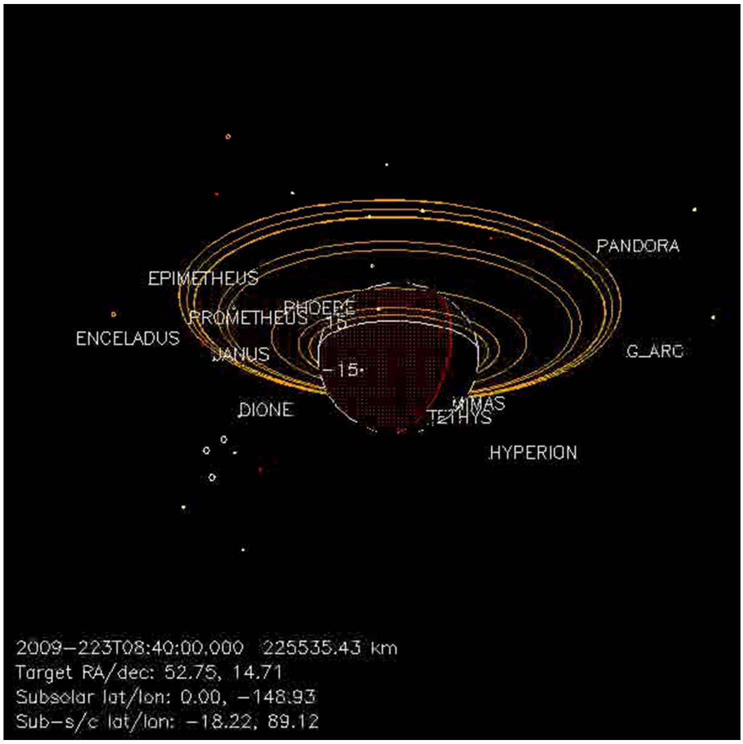

Figure 5.9. This schematic shows Saturn and its rings and inner moons against a backdrop of bright stars, some of which pass behind the rings from the point of view of Cassini. By observing the brightness of a star during such an event, called a stellar occultation, we obtain a very high resolution measurement of the structure of the ring along the occultation path. When the path closely matches the orbital motion of the ring particles around Saturn, the resolution can be as fine as a single ring particle (figure 5.10).

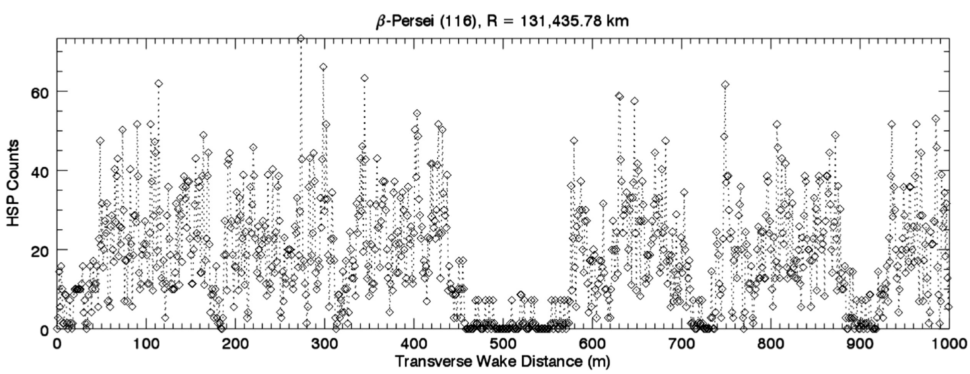

Figure 5.10. The brightness of the star β Persei is occasionally reduced to zero for long stretches as the star is completely occulted or blocked by opaque self-gravity wakes. Figure courtesy of Richard Jerousek, University of Central Florida.

5.4 Satellite wakes and shepherding

The other kind of wake in the rings truly is a wake, like the wake produced by a boat moving through the water. The moons Pan and Daphins in the Encke and Keeler gaps, respectively, near the outer edge of the A ring produce *satellite wakes* in the ring on either side of their gaps. These wakes, unlike the wake of a boat, are asymmetric. Ring particles on the inner edge of the gap orbit faster than the moon, while those on the outer edge orbit more slowly. From a vantage point on the moon, ring particles on either side of the moon travel in opposite directions. The wake is produced by gravitational perturbations on the ring particles by the moon. We are all familiar with gravity as an attractive force, but the consequences of the gravitational interaction between two objects, say a moon and a ring particle, orbiting a larger object can be counterintuitive.

Let's place ourselves on the moon Pan and consider the passage of our faster, neighboring ring particles on the inner edge of the Encke Gap some 160 km away. At that distance, the ring particles orbit Saturn in 13.820 h, while Pan takes about 90 s longer to complete one revolution of the planet. The ring particles drift past Pan at a rate of 10 m per second. Pan itself has a diameter of about 30 km, so it takes almost an hour for a ring particle at the edge of the gap to pass Pan, and 2.66 years before that same particle will have gone all the way around to lap Pan again. This time between successive encounters is called the *synodic period*. In that time, the particle will have orbited Saturn about 1685 times (and Pan will have orbited it exactly one fewer times). That's a lot of orbits, and in that time in the crowded A ring, that particle will have thousands of collisions with its neighbors and completely forget about the last time it drifted by Pan.

When it does drift by Pan, it and all of its immediate neighbors will be gravitationally attracted by Pan in a coherent way, deviating ever so slightly from their circular orbits. The eccentricity of an orbit is a measure of how much it deviates from a perfect circle. Ring particle orbits are nearly perfect circles, but the encounter with Pan gives the particle a small eccentricity. Moving closer to Pan and further from Saturn, the particle's orbital motion slows a bit so that as it completes its passage of Pan it is moving away from Pan more slowly than it was approaching Pan at the beginning of the encounter. This asymmetry between the time spent catching up to Pan and the time pulling away from Pan produces the counterintuitive result that the net effect of the encounter is for Pan to *repel* the particle rather than attract it! Here's how that happens. When the particle is catching up to Pan, Pan is pulling it forward, increasing the orbital energy of the particle. When the particle is moving past Pan, Pan is pulling back on it, reducing the orbital energy of the particle. Because the second phase of the encounter lasts longer and because the particle is a bit closer to Pan, on average, during the second phase (because it has been pulled toward Pan during the first phase), the second phase wins and the net effect is for the particle to lose orbital energy and end up on a smaller orbit, closer to Saturn (and further from Pan) than before the encounter (figure 5.11). Everything reverses for a particle on the outer edge of the gap, which orbits more slowly than Pan, so the net effect of that encounter is to put the particle on a more energetic and higher orbit,

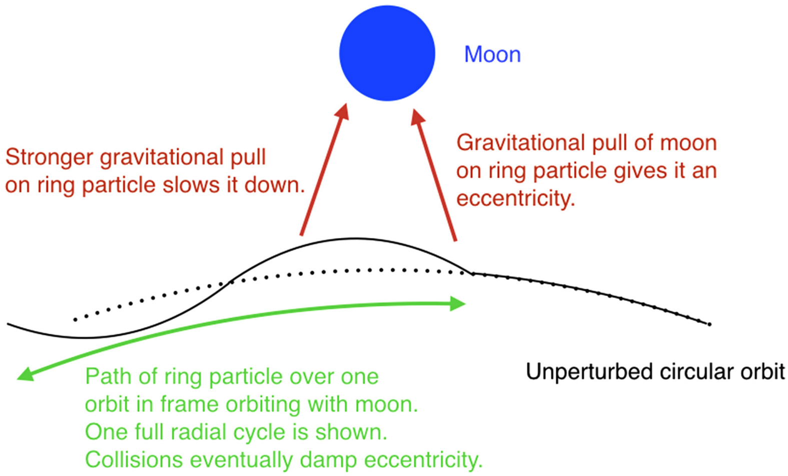

Figure 5.11. This schematic diagram of the interaction between a ring particle and a moon is in a frame orbiting with the moon. The ring particle in this case is closer to Saturn and so orbits (counterclockwise) more quickly than the moon and moves right to left in this view. The moon pulls the particle closer to it, giving the particle an eccentricity. After the particle passes the moon, it continues to pull on the particle, slowing it down. The net result is that the particle is pushed away from the moon.

again further from Pan. Thus Pan pushes the ring particles away from itself and creates a gap in the rings. This entire interaction takes a full orbit of the ring particle, during which time it is given a small eccentricity by Pan, and afterwards, collisions between the ring particles jostle them back onto parallel circular orbits again so that at the next encounter with Pan, more than two and a half years later, the process repeats (figure 5.12). Because there are a large number of particles following very similar perturbed paths, the moon creates a satellite wake on either edge of the gap. Daphnis does the same thing in the Keeler gap (figures 5.13 and 5.14). Prior to Cassini's arrival at Saturn we anticipated that many more moons would be discovered in other gaps in the rings, but extensive searches have turned up nothing.

Newton's third law of motion dictates that Pan can't push on the ring particles without the particles pushing back on Pan. If it were not within a gap in the rings, it would slowly be pushed away from the edge. As it turns out, the outer edge of the A ring itself interacts with the moons Janus and Epimetheus in just this way. The outer edge of the A ring is in an orbital resonance with these two moons who themselves are in a special orbital relationship with each other: they essentially share the same orbit and are called co-orbital satellites. The resonant interaction between the moons and the ring particles at the edge keep the particles from drifting away from each other. The resonance acts like a bookend to the rings. As with Pan and the Encke gap, Janus and Epimetheus push on the particles at the outer edge of the A ring, maintaining an abrupt ring boundary, and the particles push back on the moons causing them to slowly drift away. As they drift away, the resonance location also moves away from Saturn, and the ring edge moves outward to remain at the resonance location. Without this ring-satellite interaction, collisions between the

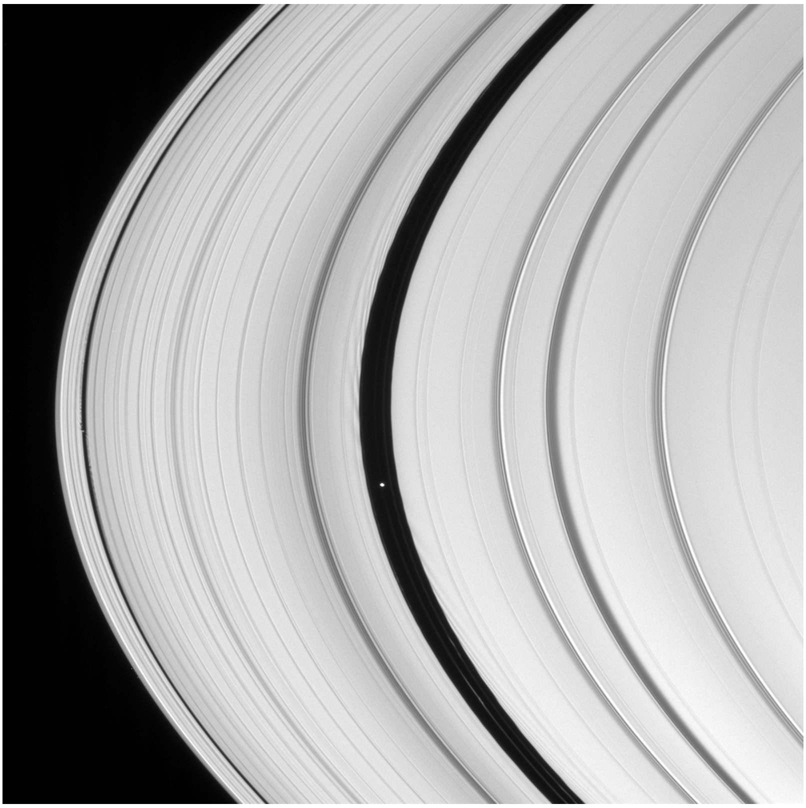

Figure 5.12. This Cassini image of the outer portion of the A ring shows Pan at the center of the Encke gap. Most of the dark circular features are spiral density waves. There are tilted features like the wake of a boat on either side of the Encke gap due to perturbations from Pan (above and trailing Pan on the outer edge, and below and leading Pan on the inner edge). The narrower Keeler gap is very close to the outer edge of the ring. Image Credit: NASA/JPL/SSI.

ring particles would cause the ring to rapidly spread out into a broader diffuse ring. At this 7:6 resonance, the approximate relation holds that particles at the ring edge orbit 7 times for each 6 orbits of Janus. As a result, the pattern of the perturbations on the ring edge has 7 lobes (figure 5.15).

5.5 Density waves and bending waves in the rings

We saw in chapter 4 that orbital resonances between objects can enhance the effects of gravitational interactions between the objects in resonance by repeating small perturbations in phase with each other over the course of many separate interactions. The simplest type of orbital resonance is called a *mean motion resonance* and is one in which ratio of the orbital periods of the two objects is equal to the ratio of two whole numbers, usually small numbers, and usually different from each other by only one or two. So, for example, a 2:1 mean motion resonance would involve one

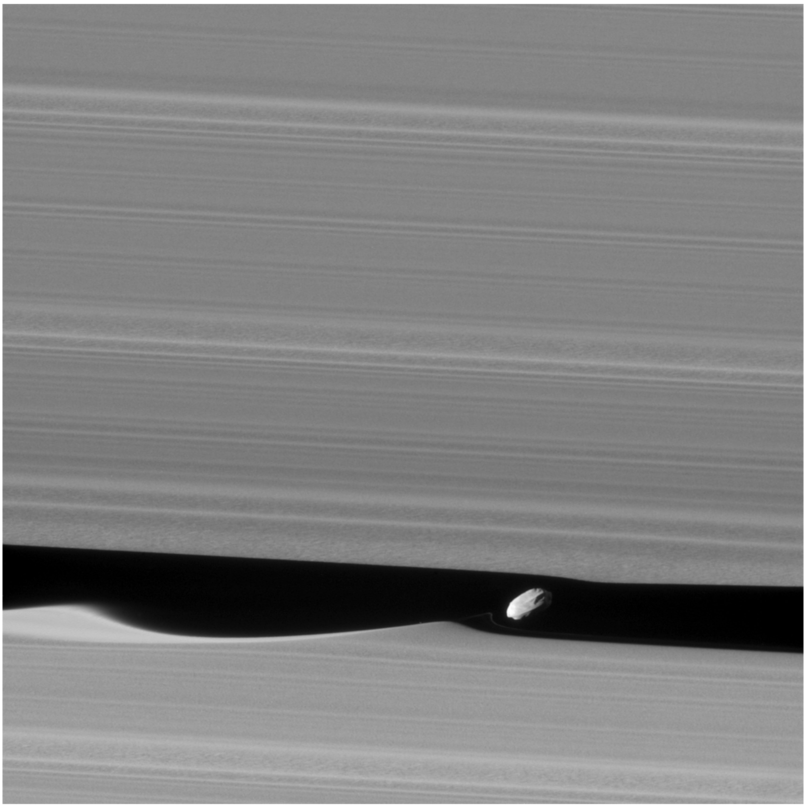

Figure 5.13. The best image of Daphnis obtained by Cassini shows the scalloping of the edge of the Keeler Gap. A narrow ringlet threads the narrow space between the moon and the edge of the gap, acting as a tracer of the dynamics of the moon, Saturn, and ring particles. Image Credit: NASA/JPL/SSI.

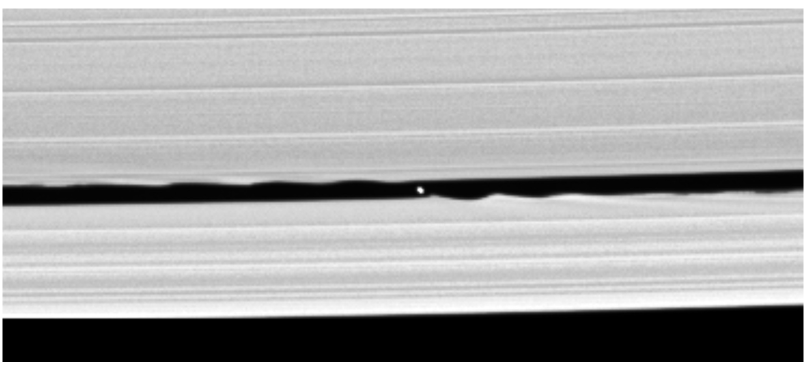

Figure 5.14. This Cassini image shows Daphnis at the center of the Keeler gap. The inner edge of the gap is towards the top of this image and orbital motion is right to left. Particles at the inner edge of the gap orbit faster than Daphnis, so particles to the left of Daphnis at the inner edge in this image have just drifted by Daphnis, and the perturbations to their orbits is evident from the scalloped appearance of the gap edge there. At the outer edge, particles orbit slower than Daphnis, so it is particles to the right of Daphnis in the image that have just encountered the moon. The particles that are about to encounter the moon (to the right of Daphnis on the inner edge and to the left at the outer edge) have not had an encounter with Daphnis in years. In that time, collisions have damped out any eccentricities so the edge is smooth and circular. Image Credit: NASA/JPL/SSI.

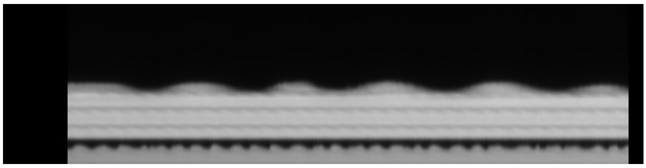

Figure 5.15. This mosaic shows most of the 7-lobe structure at the outer edge of the A ring from multiple Cassini images due to the influence of the Janus 7:6 Lindblad resonance at the ring edge. Image Credit: NASA/JPL/SSI. Mosaic and image processing by Joseph Spitale, Planetary Science Institute.

object orbiting Saturn exactly two times in the time it takes the other object to orbit exactly one time.

Things get a little more interesting due to Saturn's funny shape. The mass within Saturn is not distributed in perfect spherical symmetry (chapter 7). One consequence of this is that objects orbiting Saturn have not one but three different natural orbital periods. The one we are most familiar with is the time for a particle to complete 360° of orbital motion, and the average angular speed of an object to complete this orbital period is called the *mean motion*. An object on an eccentric orbit has a changing distance from Saturn over the course of one orbit, moving from pericenter at its closest point to Saturn to apocenter at its furthest. One complete cycle from pericenter to apocenter and back to pericenter again takes a different amount of time to complete than the time to complete 360° of motion around the planet. The time to complete this cycle is called the *epicyclic period*. Furthermore, if the object is on an inclined orbit, one that is tilted relative to the equator of Saturn, it undergoes a third periodic cycle above and below the equatorial plane (also called the ring plane). This period for vertical motion is different than the other two. When describing resonances we usually work with the angular rates of motion, also called angular frequencies, rather than the periods. The frequencies are just the inverse of the periods. For example, the Earth's mean motion period of one year means that it travels 360° in 365.25 days, so its mean motion frequency is about 1° per day. The frequencies for particles in Saturn's rings are much faster, measuring about 600° to over 1000° per day, depending on the location within the rings. At every distance from Saturn there are three natural frequencies for objects to orbit, be they ring particles or moons: the mean motion, the epicyclic (radial) frequency, and the vertical frequency. Resonances can exist with any of these frequencies, and the kind of resonance determines what sort of phenomenon will be produced.

An important type of resonance in Saturn's rings is called a *Lindblad resonance* after Swedish astronomer Bertil Lindblad. In this type of resonance, gravitational perturbations from a moon are in resonance with the radial frequency of a ring particle. This excites or enhances the eccentricities of all particles at the location of the resonance. Each time the moon passes by the ring particle, the gravitational pull it exerts on the particle is at the same phase in the particle's natural radial motion as determined by Saturn's gravitational field. It is a very subtle phenomenon with some dramatic consequences. The co-orbital moons Janu and Epimetheus are at the 7:6 Lindblad resonance with the outer edge of the A ring (figure 5.15).

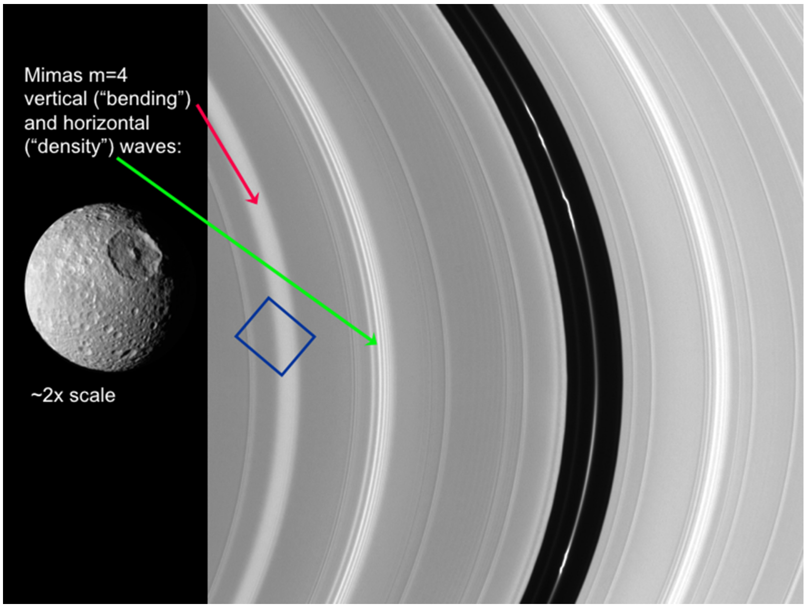

Figure 5.16. All the bright features visible in this image of the A ring in the vicinity of the Encke gap (the dark band with the narrow, irregular ringlet at its center) are waves created at resonances with moons. The two waves indicated by the arrows are both due to 5:3 resonances with Mimas (shown at roughly twice its size relative to the rings), but one is a resonance with the radial frequency of the ring particles (green arrow) and the other is with the vertical frequency (red arrow). The region in the box is shown in figure 5.19. Images: NASA/JPL/SSI.

Lindblad resonances are also responsible for producing dozens of spiral density waves in the rings (figure 5.12). These waves are the same type that give spiral galaxies such as the Milky Way their spiral arms, but in the rings the waves are wrapped around Saturn much more tightly. Each moon can have Lindblad resonances in the rings, but only those moons that are close to the rings have resonances in the rings that are strong enough to produce observable density waves. While Pan is actually within the rings, it is fairly small so the density waves it produces can only be detected through careful image processing techniques. The strongest resonances are those due to Janus, Mimas, and two moons straddling the F ring, Prometheus and Pandora (figure 5.16). These waves are identified by the number of spiral arms which is determined by the number of orbits a ring particle completes before it gets its next resonant 'kick' from the moon. This number is denoted by the letter m for no good reason, and the number of spiral arms is equal to $m + 1$ (figure 5.17). (Detailed treatment of resonances in planetary rings and planetary systems in general can be found in Murray and Dermott (1999).)

The perturbations to particles' eccentricities near the resonance produce alternating regions of more and less dense regions of the rings. The spiral density wave is produced by a combination of the periodic forcing of particle eccentricities coupled with the gravitational effect of the ring particles on their neighbors once the particles have been perturbed into a non-axisymmetric distribution

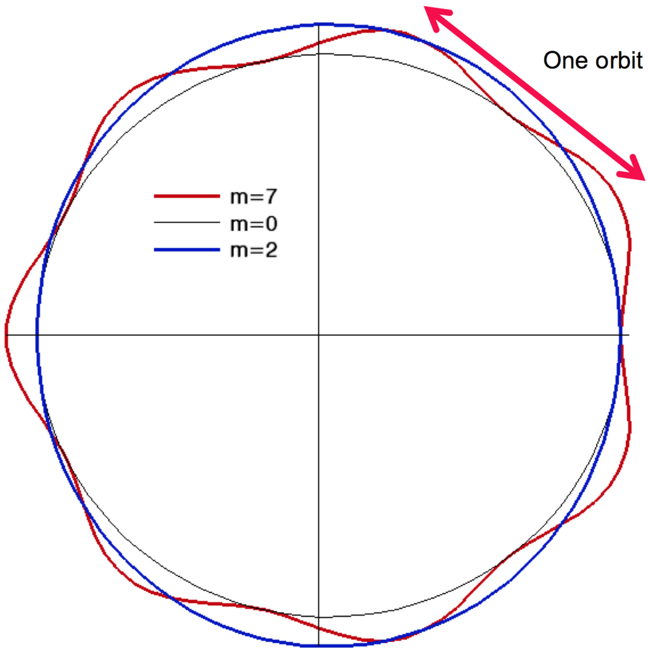

Figure 5.17. This schematic shows the paths of particles on an unperturbed ($m = 0$) orbit and two different perturbed orbits in a reference frame rotating at the rate of the perturbation. In such a rotating frame a particle makes m radial excursions before the pattern repeats. The duration of each full radial cycle is one orbit. So the $m = 7$ path shown here is 7 full orbits for the particle.

(figure 5.18). The spiral pattern is created because the radial motions of the particles have different frequencies (speeds) at different distances from the resonance. Once that pattern is created, the ring is no longer azimuthally symmetric, so ring particles feel a slight gravitational tug forward or backwards in their orbital motion due to the neighboring spiral arms. This tightens the spiral up the further one moves away from resonance. The mass of the spiral arms of the wave act on the orbits of the particles in such a way as to tighten the winding of the spiral arms. The more massive the rings are, the tighter the winding. This provides us with a very powerful tool to measure the mass of the ring, at least at the location of the wave. Prior to the end of Cassini's mission, when the mass of the rings as a whole will be measured by its perturbations on the motion of Cassini itself, this is the only tool we have to measure the mass of the rings. It is quite valuable, but it only tells us the mass where there happen to be density waves, and the density waves are most densely distributed in the A ring.

The spiral arms in the density waves are wrapped around Saturn so tightly that adjacent peaks in the wave appear nearly circular (figure 5.19). Like any wave, it is the perturbation pattern that propagates through the medium, and not the particles themselves. The ring particles find themselves moving from a wave crest, where particles are more closely packed, to a wave trough where they are less tightly

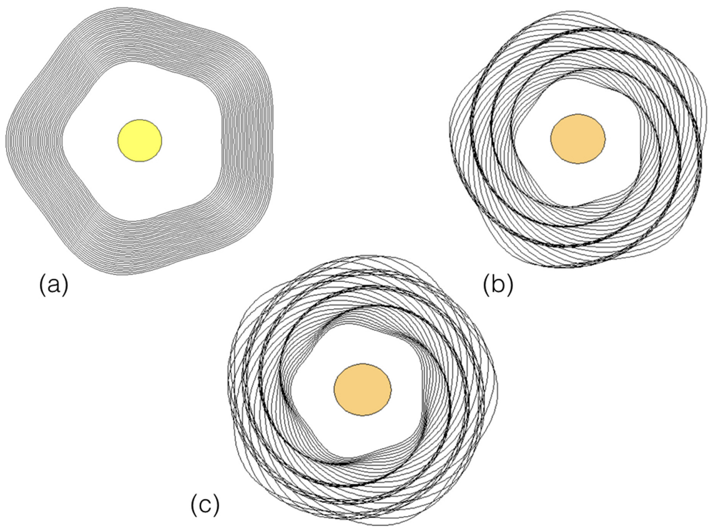

Figure 5.18. These schematic diagrams illustrate how a spiral density wave is formed from the perturbed paths of ring particles near a Lindblad resonance. An $m = 5$ Lindblad resonance puts particles on a five-lobed pattern seen in a reference frame rotating with the perturbing moon (a). The epicyclic or radial frequencies of ring particles are different at different distances from Saturn, however, so the five-lobed pattern is rotated a little bit as one moves away from the resonance location. This results in the particle paths forming a spiral pattern with $m = 5$ arms (b). The gravitational influence of the particles in those spiral arms rotates the orbits back a little, resulting in a spiral density wave where the wavelength (the distance between two spiral arms) decreases with increasing distance from the resonance (c).

packed just like a buoy on the water bobs up and down from crest to trough as a wave passes by without actually moving in the direction that wave propagates. Particles move from crest to trough and back again several times each orbit, depending on the value of m.

So, as we've seen, the Lindblad resonances occur at locations in the rings where the ring particles' natural frequency for radial motions are periodically tickled by a moon so that the perturbations add up over time. The resulting density waves are like a compression wave in a slinky. Vertical resonances occur at locations in the rings where the ring particles' natural frequency for vertical motions are periodically tickled by a moon. These are less common than Lindblad resonances because they require the perturbing moon to be on an orbit that is inclined to the rings, and the details of how these resonances work make them intrinsically more widely spaced and less strong. Mimas is on an inclined orbit and is a pretty massive moon, however, and its 5:3 vertical resonance produces a prominent wave in the A ring. This wave is a warping of the ring rather than a compression of particle orbits. It propagates in the opposite direction of a density wave (figure 5.19), and because the vertical and radial frequencies of the particles are different, the 5:3 density wave and 5:3 bending wave occur at different locations in the rings (figure 5.16). All of these

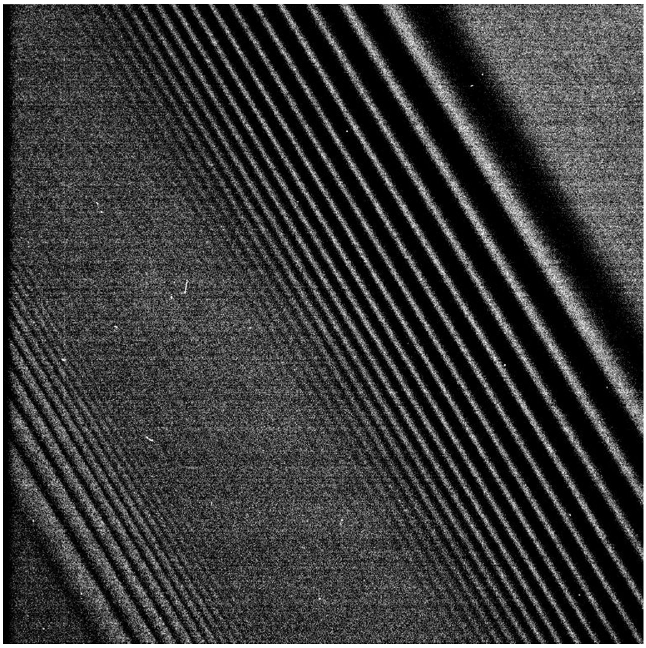

Figure 5.19. The Mimas 5:3 bending wave (right) propagates away from the moon. The wave at left is the Prometheus 12:11 density wave, propagating in the opposite direction. The direction of propagation can be determined from the changing wavelength: the wavelength gets smaller for both types of wave as distance from resonance increases. Although the wave crests appear to be parallel, they are actually part of a tightly wound spiral pattern. Image Credit: NASA/JPL/SSI.

waves in the A ring give us a pretty good measure of the mass in that ring. Assuming that our theories of how density waves work are correct, a one-square-meter chunk of the A ring (which would be 5–10 m thick) would contain a mass of about 300–400 kg, or about the mass of four people.

If you were drifting among the particles in the A ring you would find yourself in a relatively crowded region filled with bits like dirty snowballs, some as large as cars, but most the size of marbles or basketballs, likely worn down to a roughly spherical shape by countless gentle collisions. If you looked within the ring plane your view would be obscured by ring particles, but looking up or down you would see the emptiness of space a few meters away. The rings, for all their great expanse, are as thin as a sheet of tissue paper on a football field. Particles would drift slowly by you at a barely noticeable pace. Eventually you might find yourself bumping into a large elongated assemblage of snowballs, moving together but not bound to each other like the dancers in a Conga line. You might stay with this clump, a self-gravity wake, for several hours before drifting away (figure 5.20). In a density wave things would get quite crowded several times each orbit. Particles would press in on you from all sides, slowly but insistently, driven by the unrelenting distant arm of gravity.

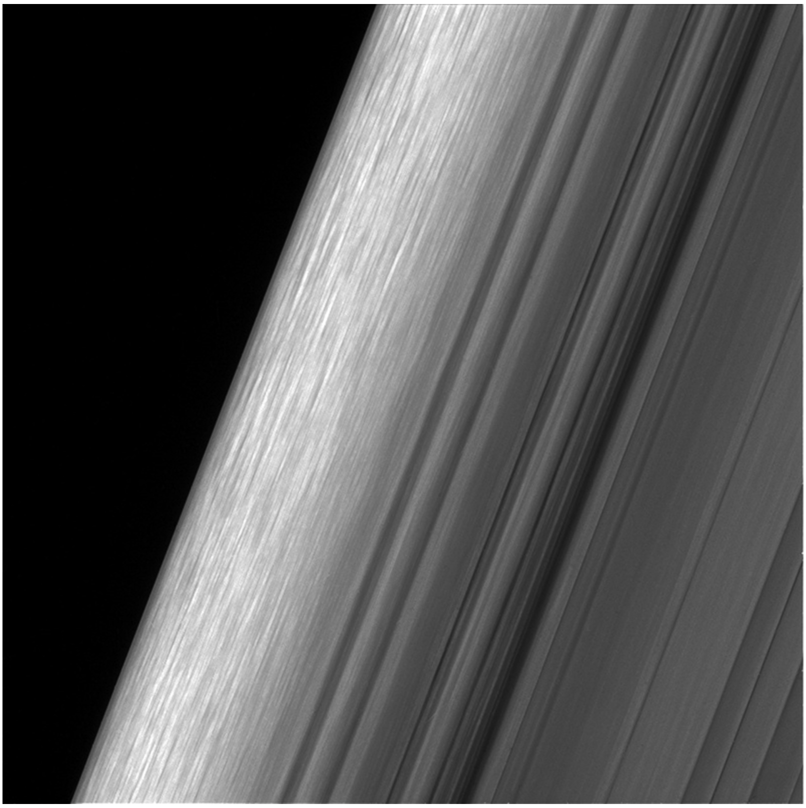

Figure 5.20. With a resolution of only 340 m per pixel, this image from the final phase of Cassini's orbital tour of Saturn shows a region of the outer A ring marked by a density wave (the dark, unevenly spaced bands at the left edge are the opaque peaks of the wave) and winding record-groove-like spiral wakes from the moon Pan orbiting in the nearby Encke gap. In the troughs between the density wave peaks the ring has a splotchy texture likely due to large temporary agglomerates of ring particles. Image Credit: NASA/JPL/SSI.

In some regions of the outer A ring you might find yourself next to a larger object, perhaps several hundred meters across. This *propeller object* might have formed from accretion of many ring particles, but their distribution in discrete bands within the A ring suggests that they may instead by the leftover largest pieces of a small moon fragmented by a cometary impact. If you came near this mini-moonlet your orbit would be strongly perturbed, and you might find yourself drifting away from it, pushed onto a different orbit by the combined interactions of the propeller object and Saturn (figure 5.11). Particles on nearly the same orbit as the object turn around, moving to a slightly larger or smaller orbit and then drifting away. Particles whose orbits are slightly different than the object receive a gravitational kick that increases the eccentricity of their orbits producing a wavy pattern on either side of the object. This two-lobed perturbation to the ring particles produces the two-bladed propeller pattern observed in the A ring around small, unresolved moonlets at their centers (figures 5.21 and 3.6).

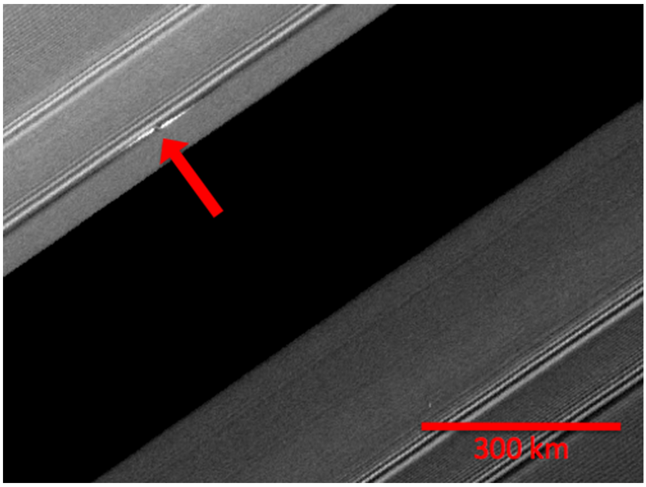

Figure 5.21. This image of the Encke Gap, the empty diagonal band, shows two density waves on either side of the gap and a prominent propeller object nicknamed 'Earhart' after the aviator Amelia Earhart. The object producing the two-lobed disturbance is too small to be seen directly, but based on models it may be nearly 1 km across (Tiscareno *et al* 2008). Image Credit: NASA/JPL/SSI.

Mimas is the largest moon close to the ring, and its resonances produce strong perturbations. Janus, while smaller than Mimas, is closer to the rings and so it has more of the strong first-order resonances in the rings. In fact, the only first-order resonance with Mimas that lies within the main rings is the 2:1 resonance[3]. For Janus, the 2:1 through 6:5 resonances all lie within the rings, and the 7:6 Janus resonance marks the boundary of the A ring. In stellar occultation data (figure 5.22) and images (figure 5.19) these waves show an almost mathematical precision. The Mimas 2:1 resonance marks the boundary of the B ring. The perturbing effects of this resonance on the ring particles is likely what has created the outer edge of the B ring and opened up the gap outside the B ring known as the Huygens Gap. This resonance is so strong that rather than launch a wave, the perturbations to the particle orbits are large enough to clear a gap. The resonance with the moon almost acts like a moon itself, opening a gap the same way Pan and Daphnis maintain gaps in the outer A ring.

5.6 The B ring, ballistic transport and spokes

The B ring edge, like the A ring edge, is not circular due to the perturbations from the Mimas 2:1 resonance. These perturbations also force the particles in the outer region of the B ring to pile into each other. The resulting crush of particles forces them out of the ring plane, producing giant piles of particles more than a kilometer high as can be seen in the stunning images taken when the Sun was shining nearly

[3] The order of a resonance refers to the difference between the two numbers of the resonance. A 7:6 resonance is first order, while a 5:3 resonance is second order. There are no first-order vertical resonances.

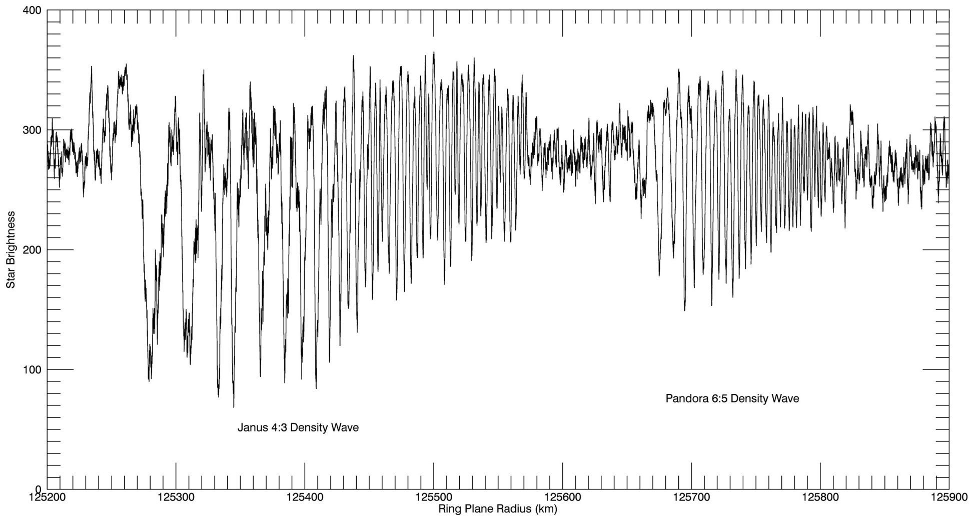

Figure 5.22. This figure shows the brightness of the star Beta Centauri as it was occulted by Saturn's rings in 2008. The occultation shows the changing density of the ring in two strong density waves, one created at the Janus 4:3 Lindblad resonance (left) and one created at the Pandora 6:5 Lindblad resonance. The wavelength of each wave decreases with increasing distance from the location of the resonance, and the rate of this change is determined by the local mass of the ring. In the Janus 4:3 wave there are 4 spiral arms wrapped around Saturn multiple times giving rise to the large number of oscillations seen in this occultation.

edge-on to the rings (figure 5.23). These images dramatically illustrate how ring particles can be coerced into clumping together to form moon-sized objects by the gravitational forcing effects of a distant moon. The changing shape of the B ring edge due to Mimas can be seen in figure 5.24 where the pattern of motion is more complicated than a simple two-lobed ellipse as would be expected for the 2:1 resonance. In addition to the Mimas perturbation, the ring is ringing, for lack of a better word, at its own natural frequencies, with waves traveling back and forth across the outer region of the ring. These waves are created not by an external moon such as Mimas, but by instabilities in the ring that lead to clumping of the particles into very dense regions separated by less dense regions. These so-called *viscous overstabilities* may be responsible for the complicated alternating structure of the transparency seen in much of the B ring (figure 5.3) (Salo and Schmidt 2010). The large clumps piled up at the outer edge of the B ring (figure 5.23) and their perturbed motions (due to Mimas) may act like pseudo-satellites with resonances in the nearby Cassini Division. The B ring edge, sculpted by Mimas, may in turn be shaping the structure and gaps in the Cassini Division, where we had previously expected to find more moonlets (Hedman *et al* 2010).

While density waves are the dominant features of the A ring, most of the structure in the B ring is not understood at all. There are regions where the ring is featureless for hundreds of kilometers (the so-called 'flat spot' in the inner B ring), regions of quasi-periodic oscillations in transparency, and regions where there seems to be no pattern in the variations of ring transparency (figure 5.3). Some of this structure may

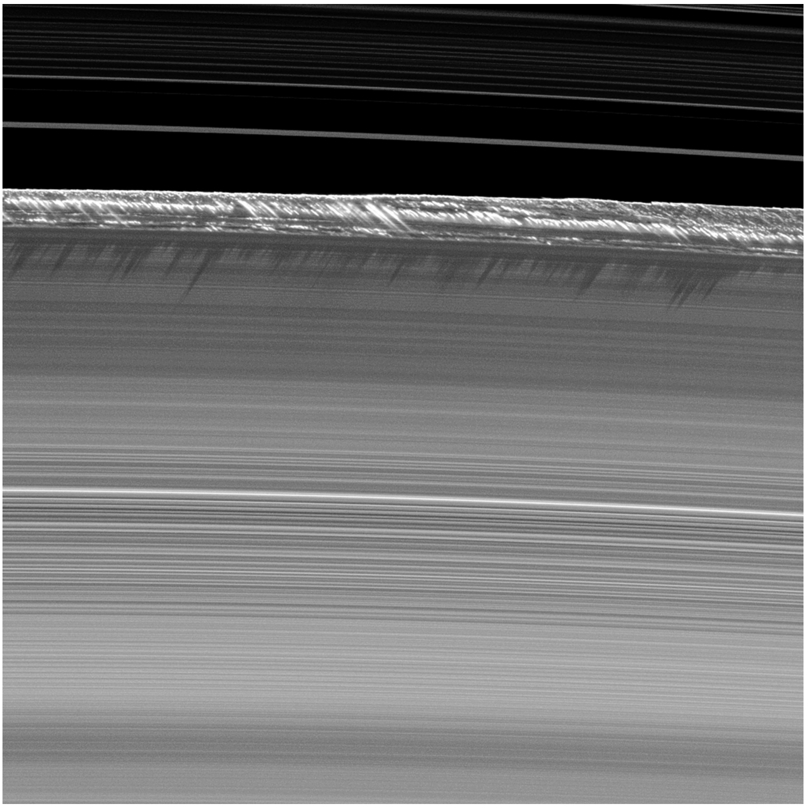

Figure 5.23. This image of the outer edge of the B ring was taken near Saturn's equinox when the Sun was shining nearly edge-on to the rings. In this geometry, things that stick out of the ring plane cast long shadows, like a building at sunset. By measuring the lengths of the shadows in this image we know that the pile-ups of ring particles at the ring edge are up to 2.5 k high, while the normal ring thickness is only a few meters. These particles are pushed inward by the resonance with Mimas, but have nowhere to go up but up (or down) and out of the ring plane. Image Credit: NASA/JPL/SSI.

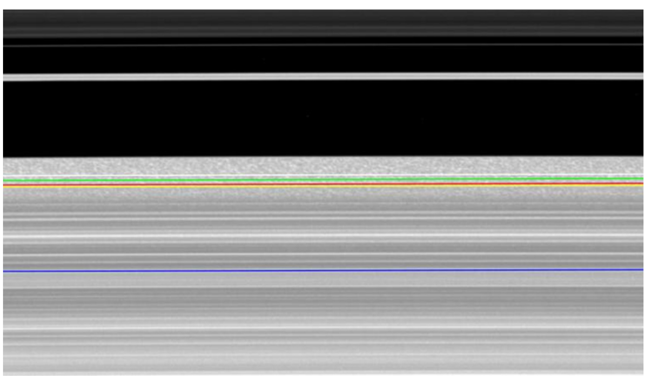

Figure 5.24. The position of the outer edge of the B ring varies with time (or equivalently with longitudinal position around the ring). The green line indicates the location of the Mimas 2:1 Lindblad resonance, and the white line is the average location of the ring edge. The other colored lines indicate reflection boundaries for natural oscillations of the ring that also shape the edge. Movie Credit: NASA/JPL/SSI.

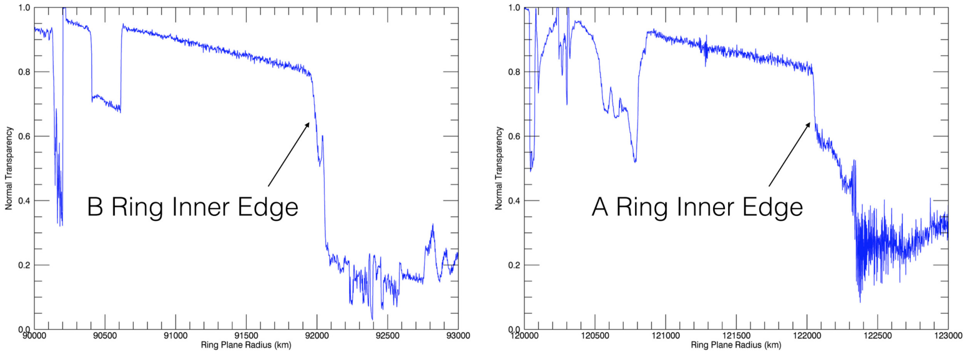

Figure 5.25. These plots show the transparency of the rings at the inner edge of the B ring and A ring measured during a stellar occultation by the Cassini UVIS.

be due to the viscous overstability mentioned above. Particle 'traffic jams' have also been suggested, in which the particles are so tightly packed that rather than orbiting Saturn independently they lock up into slabs, resulting in unusual density patterns (Tremaine 2003). Other aspects may be related to a process known as *ballistic transport* in which meteoroids striking the rings produce ejecta that reimpacts the rings at other locations. This transfers mass[4] from one location to another, and if the initial distribution of material in the ring is not uniform this process can either enhance or diminish these variations, depending on the initial conditions. This process is believed to be responsible for the structure of the inner edges of the A and B rings, which share some striking similarities. As can be seen in stellar occultation data in figure 5.25, both edges have a notch feature with a transparency of about 0.6 and then a linear 'ramp' feature that transitions to the C ring in the case of the B ring inner edge and the Cassini Division in the case of the A ring. At the bottom of the ramp there is a feature with transparency of about 0.7, followed by a narrow increase in transparency to a gap (transparency of 1), and then a narrow ringlet. All of these features are consistent with formation from the process of ballistic transport (Durisen *et al* 1989, 1992). The meteoroid impacts onto the rings preferentially launch ejecta in the orbital direction of the ring particles, enhancing a previously existing ring boundary.

One of the most surprising discoveries of the Voyager encounter with Saturn were radial features in the rings dubbed spokes (figure 5.26). Spokes appeared spanning thousands of kilometers across the B ring in regions where as few as five minutes before images showed no sign of the spokes. Particles moving only under the influence of Saturn's gravity could not travel across such a great distance so quickly. This suggested that the particles making up the spokes were small enough to be affected by the Lorentz force, the force exerted by electric and magnetic fields on charged particles. Gravity knows how to bind particles together, and the shapes of

[4] It also transfers angular momentum. The reimpacting ejecta makes the particles it hits move onto new orbits, changing the local structure of the ring.

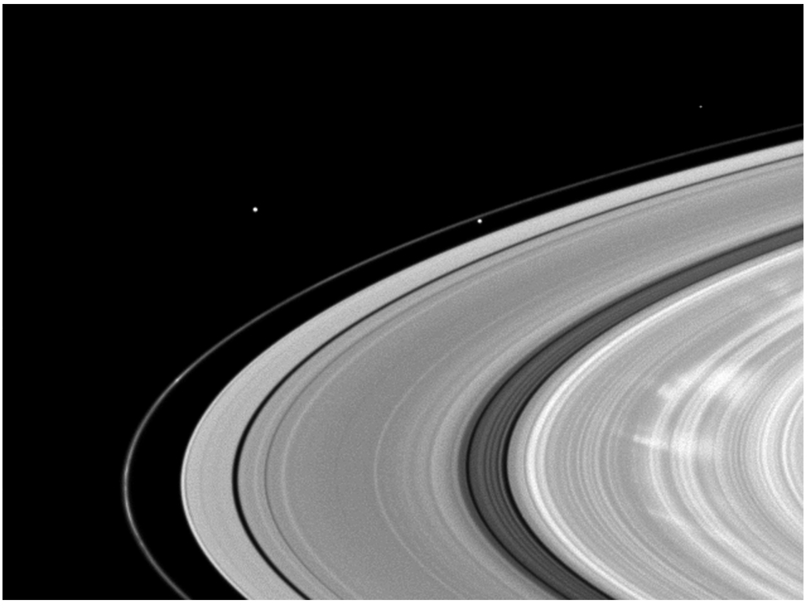

Figure 5.26. The bright spots on the right are 'spokes' that appear in the B ring and last for about one orbit before fading away. Image Credit: NASA/JPL/SSI.

their orbits are elliptical. While three-body interactions such as those due to perturbations from moons described above can produce some complicated deviations from perfect ellipses, these are just small perturbations, and the orbital speeds remain at their stately pace dictated by the distance to Saturn. Radial features streaking across the rings, apparently fleeing Saturn, and then disappearing in a matter of hours, was an entirely unexpected phenomenon and requires forces other than gravity to explain.

Saturn, like Earth, has a magnetic field that is generated in its interior. Magnetically, the planet can be roughly approximated by a bar magnet spinning around its axis. As described in chapter 4, the motion of charged particles in a magnetic field can be quite complex. While magnetic fields deflect charged particles, creating spiral motion and bouncing north and south along the field lines, an electric field pushes a positively charged particle in the direction of the field (or in the opposite direction for a negatively charged particle). The rotation of Saturn's magnetic field produces the effect of an electric field, called a *corotation electric field*, directed radially away from Saturn. This is precisely the geometry needed to explain Saturn's peculiar radial spokes.

We know from our experience of seeing houseflies safely stand on vertical walls, while dogs and cats invariably plummet to the floor, that particles must be small for the electric force to win out over gravity. Another aspect of the spoke observations supported the idea that they are small particles subject to strong perturbations from the Lorentz force. In some geometries the spokes appear darker than the

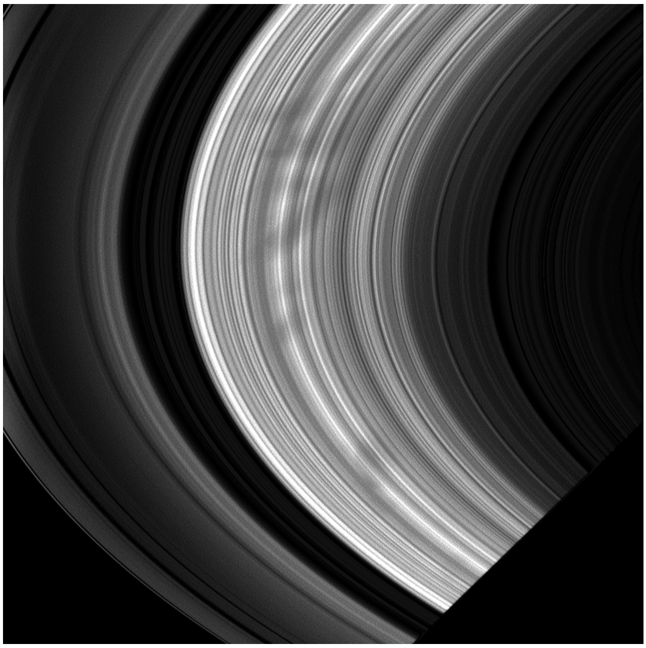

Figure 5.27. The spokes appear dark against the bright B ring in this Cassini image of the lit side of the rings. The dark diagonal line at lower right is the shadow of the planet across the rings, and the ring particle motion is clockwise in this view. The spokes are newly formed and emerging from the shadow. Image Credit: NASA/JPL/SSI.

background rings (figure 5.27), and in others they appear brighter (figure 5.26). When looking back toward the Sun the spokes are bright, but when the Sun is behind Cassini they are dark, precisely what is expected from micron-sized dust particles. Detailed modeling of the spoke brightness is complicated by the brightness of the background ring material which also depends strongly on viewing geometry, but has confirmed that the particles are about one micron (10^{-6} m) across.

Intensive imaging campaigns designed to track the formation and evolution of spokes were planned for Cassini, but when it arrived at Saturn it found the rings to be spoke-free. A clue that this might be the case was provided by images obtained with the Hubble Space Telescope during the interval between the Voyagers and Cassini's arrival at Saturn. Images showed the spokes gradually decrease in number as Saturn's season changed. The Voyagers observed the spokes when the Sun was shining on the rings from a relatively low angle, about 8° out of the ring plane. Hubble observations made with a similar solar geometry also showed the spokes, but as Saturn's seasons changed and the Sun moved further from the ring plane, the spokes faded away. At the time it was believed that this was due to our changing vantage point relative to the ring plane and the illumination of the spokes by the Sun. When Cassini failed to find any spokes at all, regardless of viewing geometry, scientists realized that the changing season at Saturn wasn't affecting the visibility of the spokes but the conditions that allow them to form in the first place.

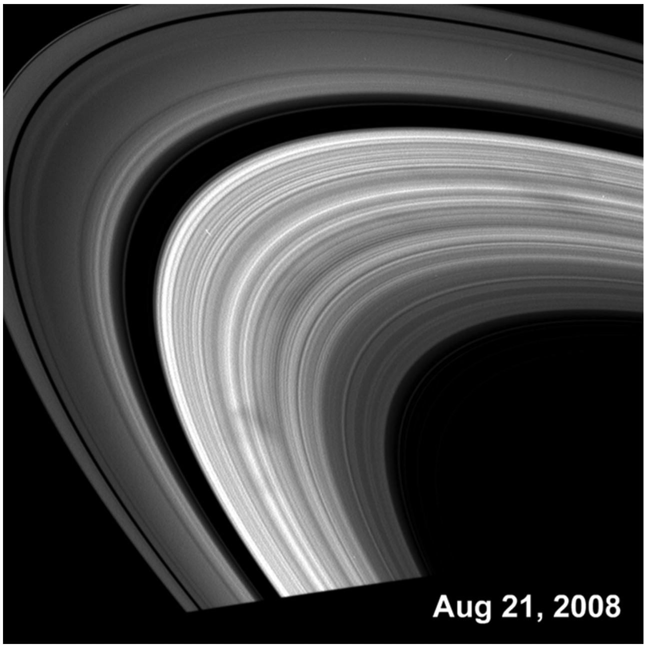

Figure 5.28. This movie made from several sequences of Cassini images shows spokes orbiting in Saturn's B ring. Movie Credit: NASA/JPL/SSI.

When the Sun shines on a surface, high-energy photons from the Sun can kick electrons off the surface[5]. These photoelectrons can produce a tenuous electron atmosphere or 'sheath' above the surface which is left with a positive charge by the departure of the photoelectrons. When it is close to mid-summer or mid-winter, the Sun shines more directly on the rings and produces more photoelectrons, while close to the equinoxes, when the Sun is close to the ring plane, photoelectron production decreases. While the details of spoke formation remain an area of active research, the changing charge of the ring plane with Saturn season controls the trajectories of the charged dust particles. One model for the spokes is that a meteoroid impact onto the rings produces a shower of micron-sized dust particles as well as a plasma of ions and electrons. The positive ions (or positively charged dust, depending on the particular model) move radially outward due to the corotation electric field. As they do so, they either charge dust on the surfaces of other ring particles, causing them to lift off the positively charged ring particles, or the initial dust particles knock off still more. But if the solar charging of the rings is too strong then these charged particles simply escape into space away from the rings entirely rather than cruise over the surface of the rings, kicking off more spoke particles. After this prediction was made, the spokes reappeared as Saturn neared its equinox in 2008 (figure 5.28). Thus, spokes appear to be a phenomenon restricted to spring and fall at Saturn.

[5] This does not happen on the Earth because the atmosphere absorbs the energetic photons before they reach the surface.

Although the details of how spokes operate are still being studied, it seems that impacts play a role in triggering them. Most spoke formation models rely on impacts onto the rings to produce either plasma, an initial spray of dust particles, or both. Spokes are also seen to form preferentially near morning in the rings, just as the ring particles emerge from Saturn's shadow. In the shadow, on the opposite side of Saturn from the Sun, the ring particles have the highest speed relative to the rest of the solar system because their orbital velocity around Saturn at that location is in the same direction as Saturn's orbital velocity around the Sun. Impacts onto the rings on the nightside of Saturn, just before morning, are therefore at a higher speed and energy because the relative speed of the ring particles and an impactor is largest there, on average.

5.7 The C ring and Cassini division

The innermost of the main rings, the C ring, shares many characteristics with the Cassini Division, the mostly transparent ring in between the A and B rings (figures 5.2 and 5.3). Based on a handful of weak waves present in each region we know that the surface mass density of these rings (the amount of mass per square meter of the rings) is at least 10 times smaller than that of the A and B rings. This has allowed the impacting meteoroids to make the particles there darker than in the A and B rings because there is less icy ring material to bury the incoming dirt in. While the C ring structure appears more orderly than that of the B ring, it is just as mysterious. Overall the C ring has a minimum in transparency of about 90% located roughly at its center, but the transparency fluctuates across the whole C ring (figure 5.3). Punctuating these gradual fluctuations are a set of about a dozen embedded ringlets[6] called plateaus with a transparency of only 60–70%, ranging in width from about 10 km to about 240 km (figure 5.29). Some of this structure may also be related to ballistic transport. The embedded ringlets immediately interior to

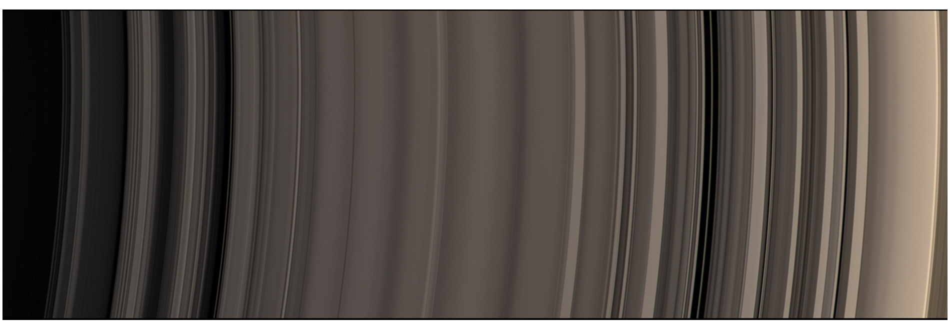

Figure 5.29. This image of the C ring shows a smoothly undulating pattern in brightness punctuated by brighter 'plateaus' in the outer half and narrow plateaus and gaps in the inner region of the ring (left). Image Credit: NASA/JPL/SSI.

[6] More or less, depending on what is identified as a plateau.

the inner edges of the A and B rings can be explained by ballistic transport and resemble plateaus (figure 5.25) (Estrada *et al* 2015).

The C ring is also home to other intriguing examples of impacts into the rings beyond the continuous hail of micrometeoroids that both darken the rings and gradually sculpt them through ballistic transport. When the Sun passed through the ring plane during Saturn's equinox of 2009, features in the rings that stuck out of the ring plane cast long shadows enabling us to observe small vertical perturbations in the rings. Matt Hedman noticed a spiral pattern in the C ring and the even-more-tenuous D ring interior to the C ring as the Sun approached the ring plane

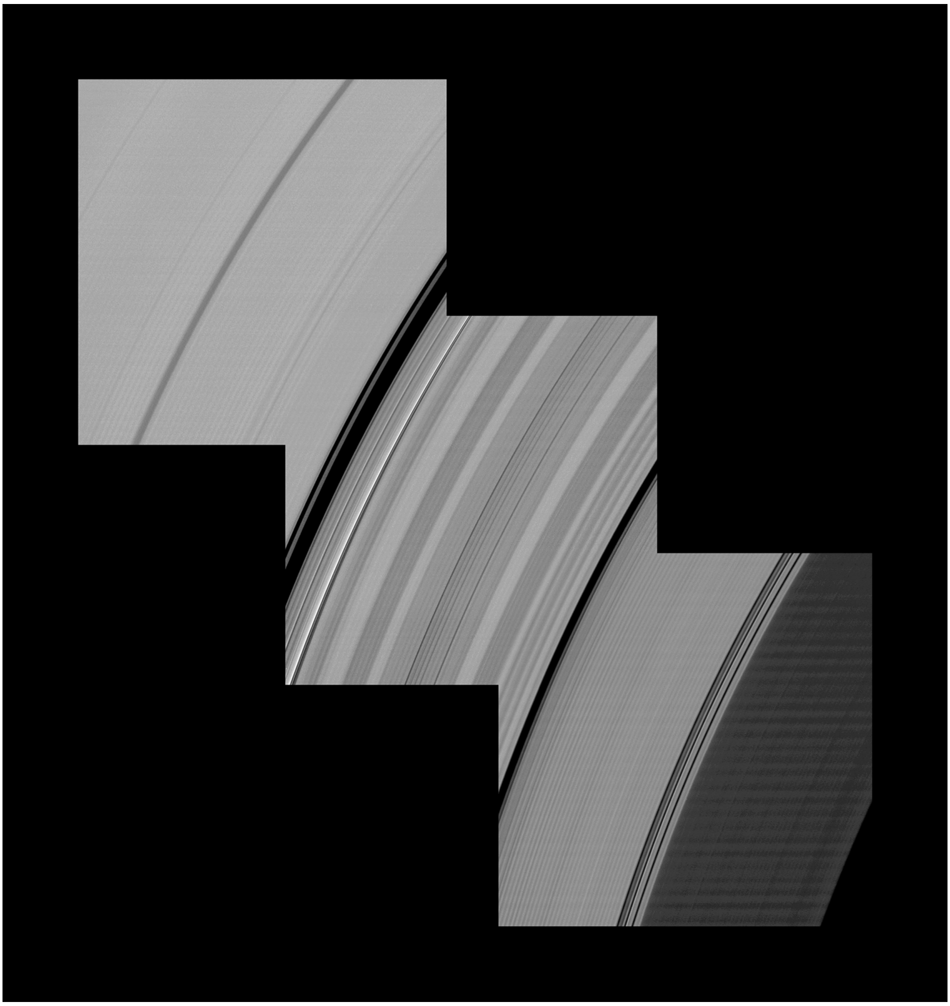

Figure 5.30. This mosaic of the D ring (dark, lower right) and C ring was taken shortly before the Sun crossed the ring plane, enhancing vertical structure in the ring. There is a periodic brightness variation that looks like the groove in a record that is only seen when the Sun is in this geometry, suggesting that it is due to particles on inclined orbits. This warping, or corrugation, extends across the entire C ring for a total width of more than 19 000 km. Image Credit: NASA/JPL/SSI.

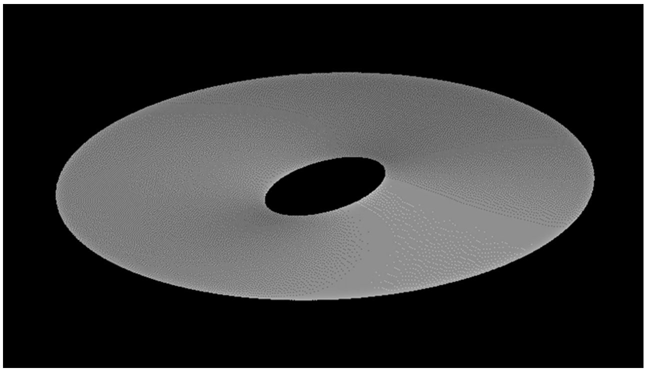

Figure 5.31. This computer animation shows how an initial perturbation to the vertical motion of ring particles across a ring evolves into a tightly wound spiral over time due to the different rates of orbital precession, or wobble, with distance from Saturn. Movie credit: NASA/Cornell.

(Hedman *et al* 2011). The spiral is caused by particles in the rings moving on inclined orbits and casting a shadow on the rings that aren't inclined. This spiral has a very different shape than the spiral bending waves produced by resonances with moons (figure 5.19). It extends from the D ring all the way across more than 19 000 km to the outer edge of the C ring (figure 5.30). The wavelength of this spiral changes not due to the gravity of the ring like in the bending and density waves described above, but due to the changing distance of the particles from Saturn itself and the passage of time.

If Saturn were a perfect sphere then if ring particles were put on an inclined orbit they would stay aligned with each other on that inclined orbit. But because Saturn is highly flattened, the vertical motion and orbital motion of the particles are not the same and change with distance from Saturn at different rates. This causes inclined orbits to precess, or wobble, with a faster wobble for orbits closer to Saturn. The spiral seen in the C ring is what would be produced if somehow ring particles across the entire ring, at one longitude, were knocked vertically out of the ring plane. All those particles would be on wobbling inclined orbits, and those closer to Saturn would wobble faster than those further from Saturn. This causes the ring to twist up into a spiral (figure 5.31). As time goes on, the spiral gets more and more tightly wound. This rate of tightening of the spiral can be calculated from our knowledge of Saturn's gravitational field and compared to the observed spiral pattern. Since the spiral tightens with time, the rate of tightening can be used to determine when the spiral winding began. The surprising answer is that something hit the rings and changed the orbits of particles across the entire C and D rings in 1983! If only we had been there to see it. The Voyagers flew by in 1980 and 1981, and Cassini arrived in 2004. The event was probably the impact of the debris from a comet, disrupted by tidal forces so that particles hit the ring over a large radial extent of the ring. Hints have been seen of the remnants of more ancient impacts in the rings, and a similar phenomenon has been seen in Jupiter's dusty ring as well.

Although the mass of the C ring and Cassini Division is too small to produce the clumping self-gravity wakes seen in the A and B rings, there are intriguing hints that particles may be accreting. Some images show streaky features in the C ring plateaus that resemble clumps seen in the strong density waves of the A ring. Analyses of many stellar occultations of the C ring and Cassini Division have found small holes in the rings that may be empty regions similar to those near propeller objects (figure 5.21) (Baillié *et al* 2013). Tidal forces from Saturn would not allow ring particles to stick to each other just from their gravity alone, so either the particles are physically adhering to each other, or they are clumping through some collective instability in spite of the low mass density of the ring. The answers to these questions, an active area of research, are relevant to the study of how planet formation got started in our own solar system and around other stars.

5.8 The F ring

While the discovery of clumping and accretion in the C ring is surprising given the proximity to Saturn, the F ring, a narrow ring just beyond the edge of the A ring lives just at the edge of Saturn's Roche zone, where tidal forces give way to accretion and the formation of moons. The F ring is straddled by the moons Prometheus (figure 5.5) and Pandora. When the F ring and these moons were first discovered it was thought that they acted as *shepherd satellites*, confining the ring particles between them via resonances in the same way that Janus confines the A ring edge, but in this case with a moon on either side confining an edge and thus maintaining a narrow ring between them. Instead it appears that the ring exists in a dynamically chaotic region where most orbits are unstable. The ring may have a very narrow (~1 km) core of large particles (meter-scale and larger) that lies between resonances (Cuzzi *et al* 2014) while the gravitational stirring due to the nearby moons causes these and other particles in the region to collide, releasing clouds of dust (figure 5.32). The ring shows a remarkably complicated structure that changes on a timescale of weeks and months (Murray *et al* 2008).

Prometheus is more massive than Pandora and also closer to the F ring, so it has the dominant effect on the ring (figure 5.32). Small objects or clouds of debris have been observed moving through the F ring region, and these objects cross the F ring,

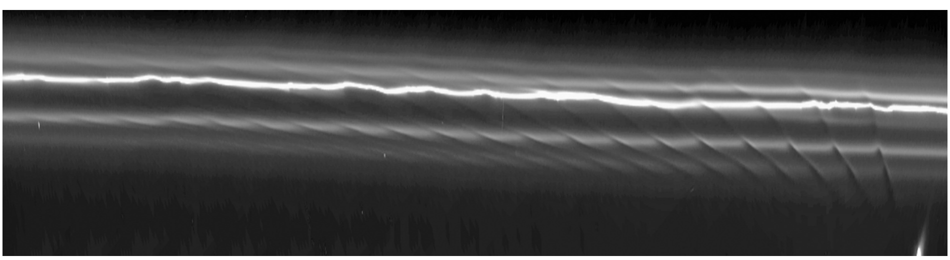

Figure 5.32. This mosaic of 15 images of the F ring has been reprojected and shows about 1/6 of the circumference of the ring (147 000 km), and the radial dimension of the image is about 1500 km. The core of the F ring is narrow, eccentric and exhibits lots of bends and kinks, and it is straddled by bands of dust that were produced by collisions within the core. The dark diagonal gores in the ring indicate recent encounters with Prometheus (partially visible at lower right) whose eccentric orbit makes it approach the F ring core every orbit, clearing out channels of particles and perturbing the orbits of the particles throughout the region. Reproduced from Colwell 2009 with permission from Springer.

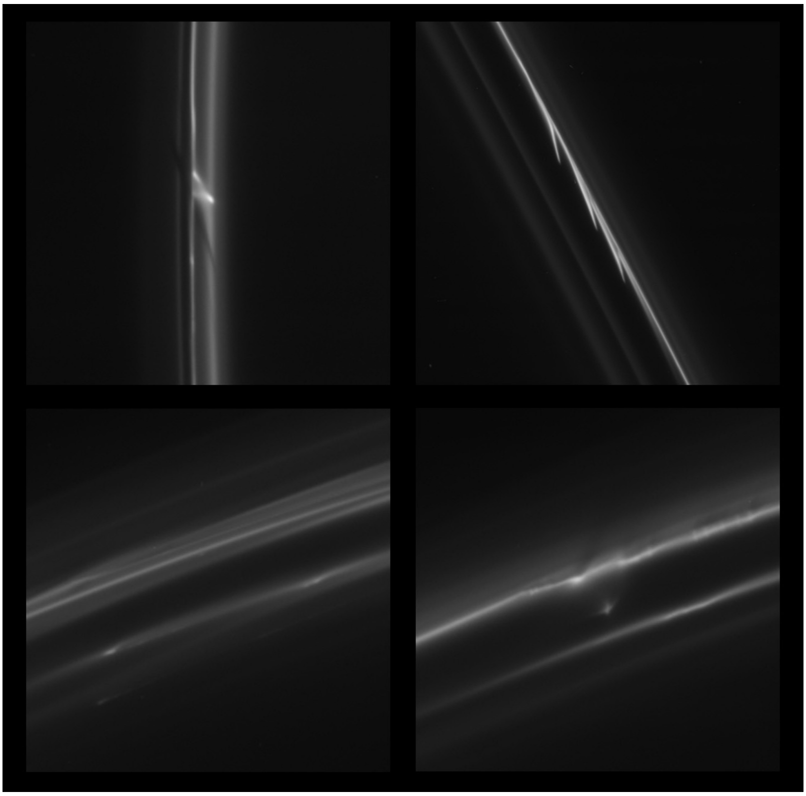

Figure 5.33. These images show features produced by collisions between objects about 1 km across with particles in the F ring core. Some of these collisions release large amounts of dust that go on to form strands all the way around the planet (figure 5.32). Image Credit: NASA/JPL/SSI.

colliding with other particles (figure 5.33). The whole area is in a state of constant accretion and disruption. Prometheus stirs the particle orbits leading to collisions which allow some of the snowball-like particles to stick together. The largest of these agglomerations may get up to one or two kilometers in size before being broken apart by a particularly energetic collision with another forming moonlet or by passing through the dense F ring core and colliding with a series of ring particles (figure 5.34).

The F ring itself is non-circular, and the orbit of Prometheus is non-circular. The different radial and azimuthal periods of particles orbiting Saturn discussed above in the context of Lindblad resonances means that an eccentric orbit precesses. That is, the orientation of the orbit changes slowly with time due to the difference between the azimuthal orbital frequency and the radial motion or epicyclic frequency. So the point in the orbit where the object is closest to Saturn, called perikrone, drifts around Saturn at a rate much slower than the time to complete one orbit. For Prometheus, the period for its perikrone direction to move through 360° is 130.6 days, while the time for Prometheus itself to orbit Saturn is only 14.7 h. The F ring itself also has a drift in its perikrone direction, but at a slightly slower rate than the drift in Prometheus's orbit, taking 133.1 days to complete a full circuit. As a result of this

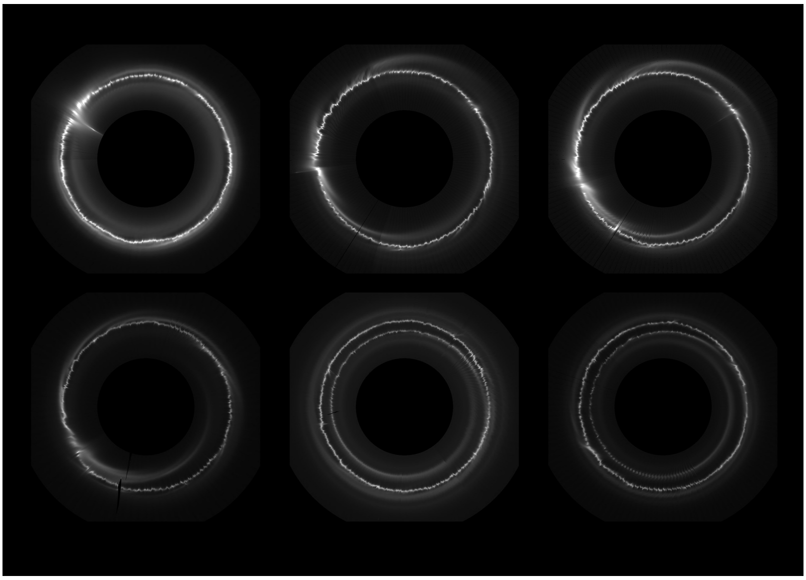

Figure 5.34. This series of montages of the F ring illustrate how quickly the appearance of the ring changes and the effects of collisions between moonlets and the ring. Each image shows the F ring reprojected as if looking down on it from above Saturn's pole, while Saturn has been removed from the images and the radial extent of the ring has been stretched by a factor of 140 to highlight structure in the ring while still making it possible to see the whole ring. The object known as S/2004 S 6 crossed through the ring shortly before the picture at upper left was taken. Debris from this collision eventually spread out around the planet forming a loose spiral that gives the ring a multi-strand appearance by 2008. Image Credit: NASA/JPL/SSI/QMUL.

slight difference in precession rate, every 19 years the two orbits are aligned, with Prometheus at perikrone at the same longitude as the perikrone of the F ring. This means that 9.5 years later, the apokrone of Prometheus will be in the same direction as the perikrone of the F ring. At that time Prometheus is at its greatest distance from Saturn at the same longitude that the F ring is closest to Saturn, and so during this time Prometheus makes its closest and most disruptive approach to the F ring. This near-collision between the F ring and Prometheus occurred in 2009 and will next occur after the Cassini mission has ended.

During the close encounter between Prometheus and the F ring every 19 years, the ring gets stirred up even more than usual by gravitational perturbations. If the edges, wakes and waves of the rings of Saturn and their relationships to Saturn's moons teaches us anything it is that gravitational perturbations can have a wide variety of outcomes. Sometimes they scatter particles away from a region, other times they may confine or concentrate particles. This happens on a large scale in the solar system's asteroid belt, where Jupiter plays the role of the perturbing moon, and the Sun plays the role of the central planet. Some resonances with Jupiter stabilize and confine asteroid orbits, producing groups of asteroids with similar orbits, while other locations are devoid of asteroids due to the scattering influence of resonances. The dynamic F ring region, stirred by Prometheus and Pandora and lying at the edge of Saturn's Roche zone, also experiences a full range of phemonena from collisional accretion of moonlets to violently disruptive collisions. Hundreds of features in the rings have been identified that are the remnants of a recent collision, usually from an unseen moonlet too small to be captured by Cassini's cameras. Some moonlets or clumps of material in the region have been detected by stellar occultations when they serendipitously pass in front of the star being observed. Voyager scientists Jeff Cuzzi and Joe Burns first deduced the presence of a broad moonlet belt throughout the F ring region from measurements of dropouts in the population of charged particles in that region of Saturn's magnetosphere (Cuzzi and Burns 1988).

The F ring lives at the boundary between moons and rings. It is constantly changing form, both spawning moonlets and destroying them. It may itself be the remnants of a moon like Prometheus that was destroyed by an interplanetary interloper or a collision with a sibling moon. Those moons may themselves have been accreted from material at the outer edge of the A ring and evolved outward due to tidal interactions with Saturn. The close relationship between rings and moons is perhaps not surprising given that each ring particle is, essentially, a small moon trying to find its way around Saturn. Without the mass of their larger companions, they make their way in a crowd, frequently jostling each other, sometimes with no consequence, sometimes joining together, and occasionally dispersing the crowd, like a police officer at a brawl.

5.9 The dusty rings

An even clearer connection between ring and moon is provided by Enceladus. The water vapor geysers at Enceladus's south pole provide a continual supply of micron-sized[7] ice grains into orbit around Saturn. Due to their small masses, these dust[8] grains are easily pushed around by interactions with sunlight. Remarkably, a micron-sized dust particle orbiting Saturn can have the shape and size of its orbit dramatically altered due to the momentum it receives from solar photons. The primary effect of this radiation pressure is to put the dust particles on highly eccentric orbits so that the dust from Enceladus covers a broad region around Saturn with the highest concentration of dust at the source (figure 5.35).

Other faint rings are visible in the right viewing geometries (figures 5.35 and 2.1), but the sources of dust in those rings is micrometeoroid impacts onto small moons knocking dust off their surfaces rather than the active geysers of Enceladus. While these rings are vast, like the Phoebe dust ring (chapter 4) they contain much less material than the main rings. The transparency of the E ring, the densest of Saturn's dusty rings[9], is more than 99.99%. The efficiency of dust production from a moon depends on the competition between the moon's surface area (a larger moon has more area for micrometeoroids to hit and knock dust off) and the moon's gravity (a larger moon has a stronger gravitational pull which prevents the ejected dust

[7] One micron or micrometer is one millionth of a meter. The diameter of a strand of human hair is about 100 microns.

[8] 'Dust' is used in planetary science to denote small particles, regardless of the composition.

[9] The F ring has a broad dusty component, but due to its core of larger objects is not usually considered in the same category as the other dusty rings.

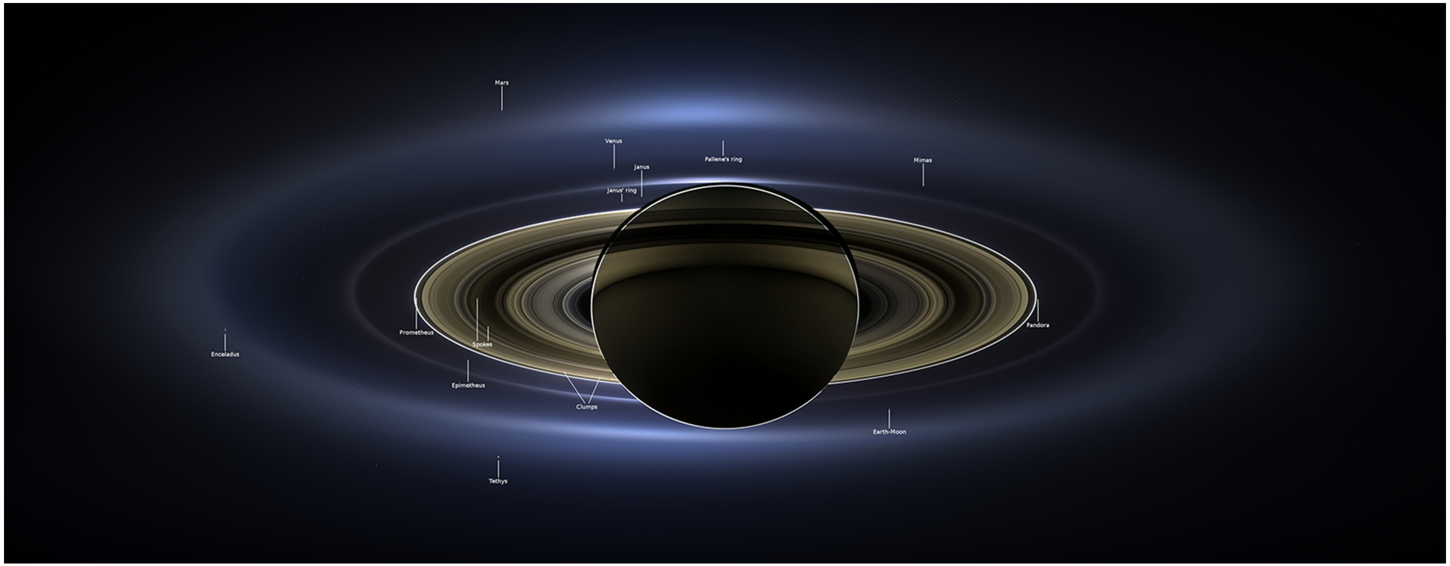

Figure 5.35. This mosaic of Saturn and its rings was taken by Cassini when the Sun was blocked by Saturn. In this geometry, looking back toward the Sun, dusty regions are particularly bright because they scatter light forward more than backward. The central B ring is dark because it is nearly opaque, while the F ring, the narrow bright ring just outside the A ring edge, shines brightly due to dust released in its collisionally active environment. Beyond the F ring are four fainter dusty rings: the very faint and narrow Janus ring, the bright G ring (unlabeled), the Pallene ring (a barely visible enhancement in the E ring), and the broad and diffuse E ring. Looking back toward the Sun, this remarkable mosaic also captured the Earth, Mars, and Venus as well as several of Saturn's moons. Although we are looking at the nightside of Saturn, the disk of Saturn is not completely dark due to sunlight reflected on its nightside by the rings. Image Credit: NASA/JPL/SSI.

from leaving the moon). Gravitational focusing of the interplanetary impactors (chapter 4) enhances micrometeoroid impact rates on inner moons. The result of these competing processes is the system of faint dust rings associated with Janus, Anthe and Pallene seen in figure 5.35. The E ring particles, launched from the geysers of Enceladus, are nearly pure water ice, and their orbits evolve to span the entire system from the outer edge of the main rings out to Titan.

5.10 The age of the rings

The rings may be only about as massive as the moon Mimas, but the surface area of the rings is about 60 000 times the surface area of Mimas. The rings should thus be particularly sensitive to the effects of impacts. In addition to the sculpting of the edges of the A and B rings by ballistic transport and the creation of spokes, impactors from interplanetary space contribute non-icy material to the rings that should gradually darken them. If we assume that the rings began as pure water ice (an extreme assumption to provide a limiting case on the age of the rings), then in principle we can calculate their age from knowledge of the rate of impacts onto the rings. Similarly, if we assume an initial sharp edge for the inner edges of the A and B rings, the impact rate onto the rings combined with a model of ballistic transport could tell us how long it would take the edges to evolve to their current shapes (figure 5.25). The key is to measure the rate of impacts onto the rings.

One of Cassini's dozen scientific instruments is the Cosmic Dust Analyzer (CDA). The CDA has a metal target the size and shape of a large salad bowl beneath a set of wire grids. When a dust particle strikes the target, its speed is so great that it creates a tiny puff of plasma, and those charged particles are collected by the wire grids, producing a current that the instrument electronics measures. The magnitude of the electrical signal is related to the mass and speed of the impacting particle. Also, if the incoming particle is electrically charged (and most are, due to solar photons knocking electrons off of them), it produces a small signal in the grids as it passes through them, providing additional information on the incoming velocity of the particle. Through painstaking analyses of years of data, the CDA team has been able to separate out those signals due to interplanetary particles from the far more abundant impacts from dust particles orbiting Saturn. These data show that the meteoroid flux would be expected to darken an initially pure ice ring to its current reflectivity in only about 100 million years. But this conclusion comes with a number of caveats and assumptions about how much ejecta is produced by a meteoroid impact, the composition of the impacting material, and how massive the rings are. If the rings are massive enough, it may be possible for the dark meteoroid material to be covered over by clean ring ice, making the rings appear younger than they actually are.

As we've seen, the structure of the rings is intimately linked to the nearby and embedded moons. Some of these moons, such as Pan, are not expected to have survived bombardment by comets for the age of the solar system. Many of the others, such as Pandora and Prometheus, are in orbits that are not stable over the age of the solar system and are also vulnerable to disruptive impacts by comets. All of the moons are on orbits that are tidally evolving, and as their orbits evolve so do the locations of their resonances. And as the resonances go, so go the rings. Whether the rings are ancient or relatively youthful, it is certain that their appearance and structure has evolved significantly since their formation and that they will continue to evolve.

Left to its own devices, a disk of particles orbiting a planet will gradually spread. This is a consequence of collisions between the particles which are not perfectly elastic. That is, some of the mechanical energy of the particles prior to the collision is converted to minute quantities of heat at the contacts between the particles. This has the net effect of removing mechanical energy from the particles' orbits causing the orbits to decay. At the same time, the angular momentum of the system of particles is conserved. Collisions between the particles do not change their total angular momentum, so as one particle's orbit is smaller after a collision, the other's must be larger. The net effect is for the center of mass to gradually drift in, but the width of the ring to increase and the outer edge to expand. While the rings themselves are likely the debris of some progenitor object, whether a moon or a large captured comet, it is possible that the spreading evolution of the ring itself created some of the moons that now in turn sculpt the rings. As collisions cause the ring to spread, the outer edge approaches the edge of Saturn's Roche zone, where tidal forces cease to be effective at inhibiting accretion. Small clumps of ring particles may accrete with each other and spall off the edge of the ring, and then tidally evolve further outward, collecting more material that evolves outward from the ring edge. We see in the images of the small ring moons that they have accreted small particles from the rings (figures 5.4–5.6). Perhaps some of these moons are made entirely of ring particles in the first place.

Fortunately, at the end of its mission in the summer of 2017, Cassini will carry out a series of orbits that bring the spacecraft very close to the planet. By tracking the changing frequency of Cassini's radio signals as Saturn's gravity accelerates and decelerates it during each orbit, the mass of the rings can be separated from the mass of the planet and measured to high precision. Knowing the mass of the rings will help settle the nettlesome open question of just how long Saturn has had its spectacular rings.

Further reading

Planetary Rings by L W Esposito (2nd edition, Cambridge University Press) reviews planetary ring physics and the ring systems of all giant planets and has comprehensive references to the technical literature.

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Chapter 6

Titan: the planet moon

Worlds can be categorized many different ways. This is why we have so many confusing and overlapping names for them, such as planets, minor planets, moons, dwarf planets, asteroids and comets to list just the most common categories. It is also why there is a ridiculous debate about how many 'planets' there are in the solar system. One way of categorizing them is by the presence or absence of an atmosphere. Almost every world is airless: a solid mass, either icy, rocky or metallic in bulk, that has no atmosphere and whose surface is exposed directly to space. Four notable exceptions are the four largest planets, and they are essentially *entirely* atmosphere. While the state of the material deep in their interiors changes from gaseous to solid, there is never really a surface to speak of. And then there are a handful of worlds that have a surface that is protected by the comforting blanket of an atmosphere. Our world and its nearest neighbors Mars and Venus fall in this category. The only other world with a surface we could stand on and an atmosphere substantial enough to hide stars in the daytime is Saturn's moon Titan. There are only two worlds in the solar system where a human can survive on the surface without a pressure suit: Earth and Titan[1]. Titan has an atmosphere with many similarities (and some crucial differences) to that of Earth. It is mostly composed of molecular nitrogen (N_2), and the atmospheric pressure at the surface of Titan is about 1.5 times that at sea level on the Earth. Like water on the Earth there are molecules in Titan's atmosphere that can form clouds and rain that contribute to lakes in its polar regions. Vast fields of dunes are formed by its weak winds. To understand Titan, we must understand the basics of how atmospheres work.

[1] A pressure suit, or more commonly a spacesuit, has an airtight seal maintaining enough air pressure on the inside to permit a human to survive. On Titan the temperatures are so low that contact with its air would cause instant tissue death, but as long as one is covered and heated and has a supply of oxygen, the suit would not need to be pressurized or airtight. On the surface of Venus the atmospheric pressure is the same as being 900 m below the surface of the oceans on Earth. However, at an altitude of 50 km in the atmosphere of Venus the pressure would be Earthlike and the temperature like a cold winter day, but the air would still be lethally devoid of oxygen.

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6.1 The atmosphere

Atmospheres are hit from above by sunlight and the solar wind and, if the moon is within a planet's magnetosphere like Titan is, the atmosphere is also hit by charged particles trapped in the planet's magnetosphere. The bottom of the atmosphere is bounded by the surface of the world, Titan in this case. The story of atmospheres is the story of the transportation and exchange of energy between these two boundaries at the top and bottom of the atmosphere. One thing the Universe hates is sharp gradients in energy. Put a hot thing next to a cold thing and energy will move from the hot thing to the cold thing until the temperatures even out. The greater the difference (the gradient), the faster energy will flow. Atmospheres absorb energy at the top and the bottom and what goes on in between is a complicated mediation between those two energy sources involving chemistry, radiation and fluid dynamics.

Molecules, like the individual atoms they are composed of, can absorb or emit energy only in discrete quantized amounts depending on the type of molecule. There are three main types of energy levels in a molecule: electronic, vibrational and rotational. Electrons within an atom can be excited to a set of discrete energy levels by absorbing exactly the right amount of energy from a photon of light. Because the energy of a photon is uniquely determined by the color, or wavelength, of the light, that means only certain colors of light can be absorbed or emitted by any particular atomic element. In addition to these 'electronic' transitions, molecules can also exchange energy by changing their rotational state or their vibrational state. Our normal intuition for macroscopic objects is not correct for molecules. They cannot spin at arbitrary rates like an ice skater can. They can only spin at a finite set of discrete spin rates, each one corresponding to a specific rotational energy, and in turn that energy corresponds to a specific wavelength of light. The same is true for the vibrational states. Each type of oscillation of the atoms in a molecule, like masses on the ends of a spring, is governed by quantum rules as well. It is this remarkable relationship between energy, the wavelength of light, and the behavior of atoms and molecules that enables us to learn so much about the Universe simply by studying the patterns of light from distant objects. Every pattern of light emitted or absorbed by something is related to the molecular composition of that thing, and it is altered by the motion, temperature, and physical state (solid, gaseous, ionized) of the material as well. Spectra, the maps of light from an object, are packed with information.

The energy levels associated with electronic transitions usually correspond to ultraviolet wavelengths of light, while those due to vibrational states are generally in the infrared part of the spectrum[2]. Rotational states are important in the infrared part of the spectrum for molecules that have a complicated shape like methane (CH_4) and less so for simple molecules like N_2. The top of the atmosphere is hit by the full solar spectrum, from short wavelength x-ray and ultraviolet radiation to long wavelength infrared radiation. The Sun is brightest in the visible portion of the spectrum, but the shorter x-ray and UV wavelengths carry more energy per photon. Those energetic, short-wavelength photons are absorbed by atoms and molecules at

[2] Short wavelengths correspond to higher energy photons, and lower energy photons have longer wavelengths.

the top of the atmosphere. The upper atmosphere is heated by this radiation to high temperatures. This is true of all planetary atmospheres because all gases can absorb these short wavelength photons. In addition, solar wind particles (electrons and protons streaming outward from the Sun) and electrons and ions within Saturn's magnetosphere can impact atoms and molecules in the upper atmosphere causing them to break apart into different molecules or their constituent atoms or to glow when they absorb energy from the particles and then release that energy in the form of photons. This is the process that gives rise to aurorae on Earth and on other planets with magnetic fields that can concentrate the flux of charged particles onto certain areas of the atmosphere (see chapter 7 for Saturn's aurora). Without this concentrating effect there can be a more diffuse glow high in the atmosphere called *airglow* or diffuse aurora (figure 6.1).

At the bottom of the atmosphere, the solid surface of Titan radiates its own spectrum of light upward. That spectrum is determined by the temperature of the

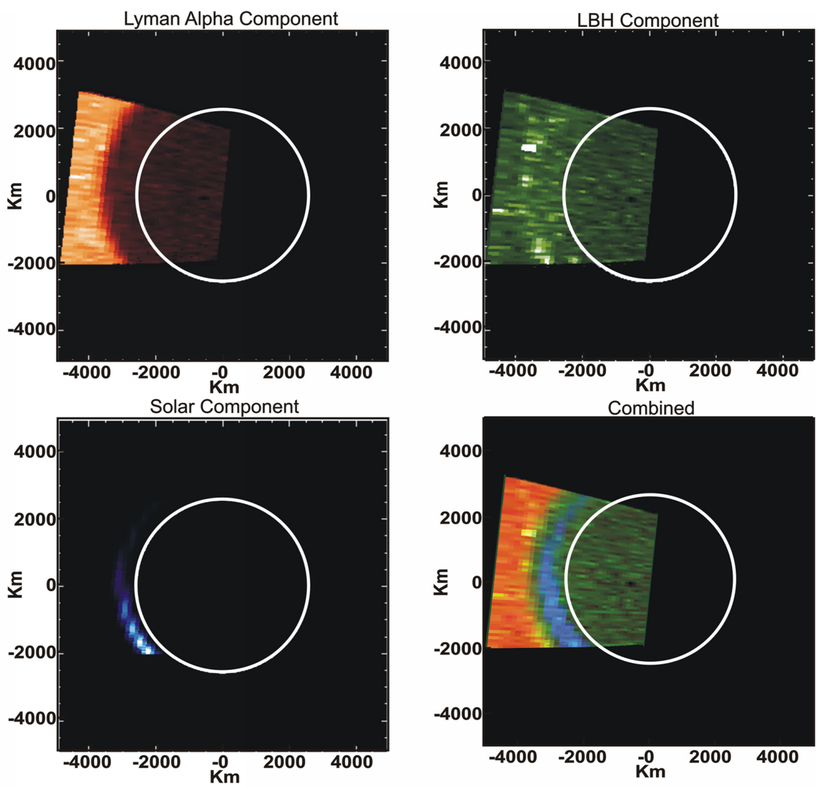

Figure 6.1. These are ultraviolet images of Titan taken by the Cassini Ultraviolet Imaging Spectrograph. The white circle shows the size of the solid body of Titan. The lower right image is a composite of the other three which use different parts of the UV spectrum. The Lyman Alpha component (upper left) shows the shadow of Titan and its extended atmosphere against the diffuse glow of interplanetary hydrogen. The LBH component shows airglow emission in the UV from the upper atmosphere, while the solar component shows reflection from haze layers in the upper atmosphere. Image Credit: NASA/JPL/Univ. Colorado/Kris Larsen.

surface. The hotter the surface, the shorter the average wavelength of the radiation. The surface of the Earth is about 290 K and the peak wavelength of the Earth's radiation to space is about 10 microns[3]. The surface temperature of Titan is about 100 K, and the peak wavelength of its radiation is about 30 microns. Diatomic molecules, such as molecular nitrogen (N_2) which makes up the bulk of Titan's (and Earth's) atmosphere, do not have rotational energy transitions in the near infrared part of the spectrum, but molecules such as H_2O (water), CO_2 (carbon dioxide), and CH_4 (methane) that have complex, asymmetric structures, have multiple rotational energy transitions in the near infrared. They are known as *greenhouse gases* because planetary surfaces cool off by radiating energy in the infrared part of the spectrum (wavelengths longer than 1 micron), and these gases absorb those wavelengths of light. This traps heat in the atmosphere and prevents the radiation from escaping to space. A greenhouse gas is like a blanket: it prevents heat from leaving a world. Greenhouse gases are transparent in the visible part of the spectrum, however, where the incoming energy from the Sun is concentrated. Thus, heat in the form of solar radiation gets through the atmosphere to the planet, but it has a hard time getting out in the form of infrared radiation that greenhouse gases absorb. This is how the *greenhouse effect* in an atmosphere works[4].

Although N_2 is not a greenhouse gas, Titan's atmosphere is a few percent methane. The greenhouse warming provided by methane is essential to maintaining temperatures warm enough for N_2 to remain a gas in the atmosphere. Without this greenhouse warming, Titan's atmosphere would be far less dense than our own. As we journey up from the surface of Titan there is less and less methane to trap radiation from the surface, and so the temperature drops until it reaches a minimum at what is called the *tropopause* (figure 6.2). The layer of the atmosphere between the surface and the tropopause, the *troposphere* is where most weather occurs because the decreasing temperature with altitude allows convection to carry warm, wet air upward, like the rising bubbles in a pot of boiling water. As we approach the tropopause the temperatures are lower, and the wet stuff may condense into clouds. On Earth the wet stuff is H_2O. On Titan it is methane and ethane (C_2H_6). Convection is much weaker in Titan's atmosphere than in the Earth's, in part due to the much lower amount of solar heating reaching the surface. Saturn (and Titan) is ten times further from the Sun than the Earth so the flux of energy, the amount of energy hitting a surface each second is 100 times less. Titan's global haze further reduces the amount of sunlight reaching the surface. The difference between daytime and nighttime temperatures on Titan is only 1.5 K[5]. Seasonal temperature variations and temperature variations from equator to pole are only slightly larger (Cottini *et al* 2012).

[3] The visible part of the spectrum (where humans can see) is about 0.4 to 0.7 microns coinciding with the peak of the Sun's spectrum at about 0.5 microns.

[4] A botanical greenhouse also lets sunlight enter (via its transparent glass roof), but the heat is trapped primarily by the physical barrier of the roof preventing convective cooling (the expansion and rising of warm air) rather than the prevention of infrared radiative cooling.

[5] A temperature difference of 1 K is the same as a temperature difference of 1 °C.

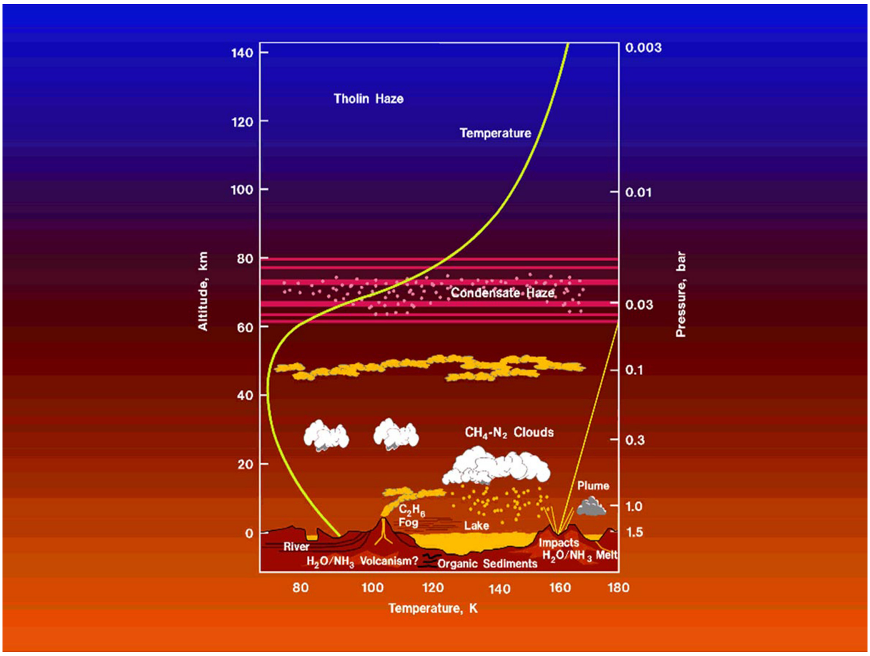

Figure 6.2. Temperature and structure of Titan's atmosphere. NASA/JPL.

As we continue to move up in the atmosphere, above the tropopause, the atmosphere begins getting warmer again, even as the atmospheric pressure and density continue to decrease (figure 6.2). This is due to warming from above: the upper atmosphere is heated by energetic solar photons that are absorbed before making it deep into the atmosphere or to the surface. Here, in the upper atmosphere, there is a different kind of rain. Hydrocarbon gunk produced with the help of those energetic solar photons as well as energetic electrons from the Sun and from Saturn's magnetosphere is formed, producing a global haze layer. There is another striking difference between Titan's atmosphere and Earth's. Titan's weaker gravity (about one-seventh of the Earth's, slightly less than that on the Earth's Moon) means the atmosphere extends to much greater heights than the Earth's. At 140 km altitude, for example, Titan's atmospheric pressure is about 0.2% of the surface pressure. That same pressure is reached at the Earth at an altitude of only about 42 km, while at 140 km above the surface of the Earth the pressure is down to 5 billionths of the surface pressure.

The chemistry of hydrocarbons can be quite complex due to carbon's ability to form very large molecules. In the upper atmosphere, methane is broken apart by solar photons and electrons, and the constituent pieces recombine to form larger molecules with a greater ratio of carbon to hydrogen than the 1:4 ratio in methane (CH_4, figure 6.3). Some of the hydrogen atoms, being low-mass and therefore moving faster than carbon and the heavier molecules at a given temperature, escape into space. The large hydrocarbon molecules that form from the byproducts of

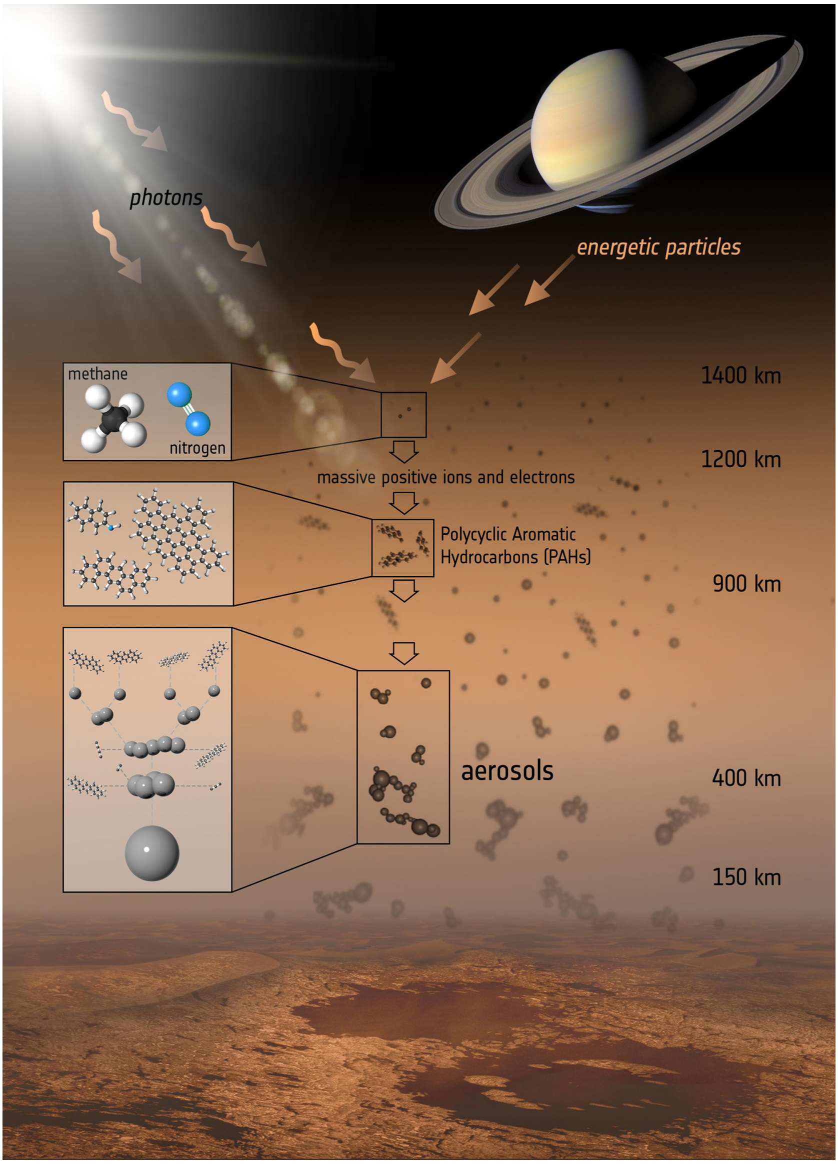

Figure 6.3. This schematic shows the formation of large organic molecules called polycyclic aromatic hydrocarbons (PAH), as well as particulate aerosols that make up the haze on Titan, obscuring its surface from view. Note the difference in altitudes compared to figure 6.2. Image Credit: ESA/ATG medialab.

methane can form microscopic particles called aerosols that make up Titan's haze layers (figure 6.4). The haze is what makes it particularly difficult to see the surface of Titan from space at visible wavelengths. Clouds are actually much rarer on Titan than on Earth (figure 6.5).

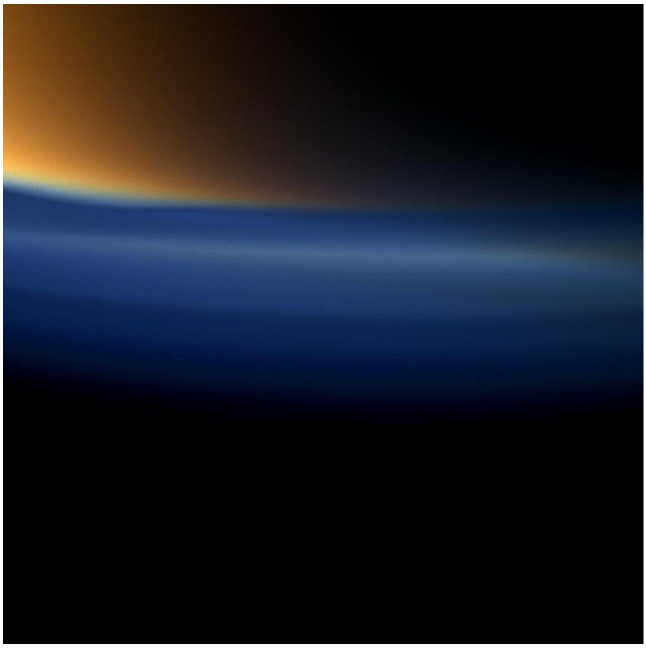

Figure 6.4. This view of the south polar region of Titan shows multiple high altitude haze layers that appear bluish, and the main atmospheric haze layer which gives Titan its distinctive orange coloration. There is a kink or depression in the haze layers near the south pole that may be related to seasonal changes. This natural color image was taken in September 2011, shortly after equinox. Southern winter is beginning, and a polar vortex may be forming in the south, resulting in the depression in the haze altitude. Image Credit: NASA/JPL/SSI.

6.2 Lakes, dunes and mountains

Titan and Earth are the only bodies in the solar system with bodies of liquid on their surfaces, though the amounts are vastly different. The evidence for liquids on the surface of Titan was tantalizing and contradictory for many years prior to Cassini's arrival. The Huygens atmospheric probe that Cassini carried to Titan was designed to float in a hydrocarbon sea, but that capability turned out not to be necessary. The equatorial region of Titan where Huygens landed does not appear to have liquids on the surface now, though there are features reminiscent of rivers and shorelines suggesting enough liquid flowed in the not-too-distant past to carve these channels (figure 6.6).

The difficulty in determining if there is liquid on the surface stems in part from the global haze layers that obscure the surface from view in visible light (figure 6.7). In certain wavelength 'windows' in the infrared, the atmosphere is much clearer, and surface brightness variations can be seen, but it is not clear just from these variations whether the surface is liquid or not (figure 6.5). The landscape near where the Huygens probe landed looks like it is crossed by fluvial features, yet Huygens came to rest on dry ground. Accelerometer data from Huygens indicates that it may have punched through a thin crust on the surface, leading the penetrometer team to famously compare the surface texture to crème brûlée (Lorenz and Mitton 2010).

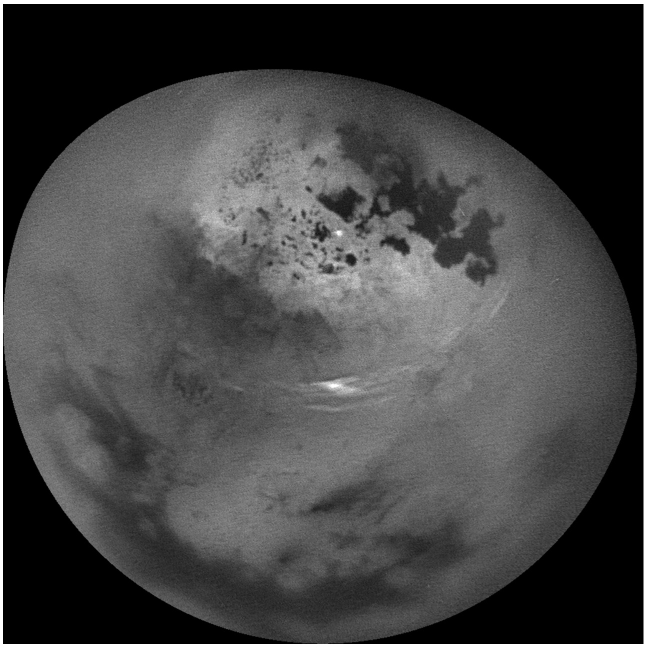

Figure 6.5. Thin clouds can be seen circulating around the north polar region of Titan in this series of images. Dark hydrocarbon lakes dot the polar region. Image Credit: NASA/JPL/SSI/Univ. Arizona.

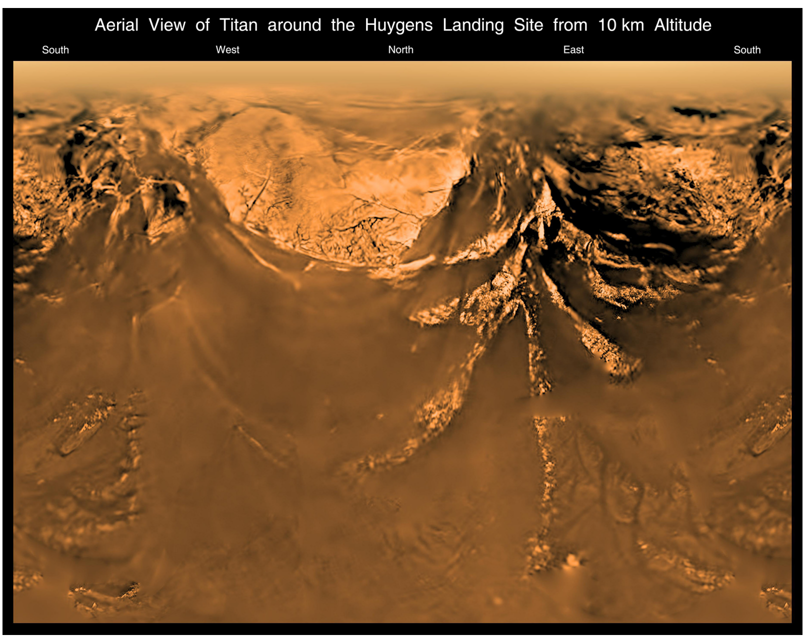

Figure 6.6. As the Huygens probe descended through Titan's atmosphere, cameras captured views in all directions. This mercator projection from an altitude of about 10 km reveals a complex landscape absent of impact craters but showing channels reminiscent of rivers and a shoreline towards the northwest. Image: ESA/NASA/JPL/Univ. Arizona.

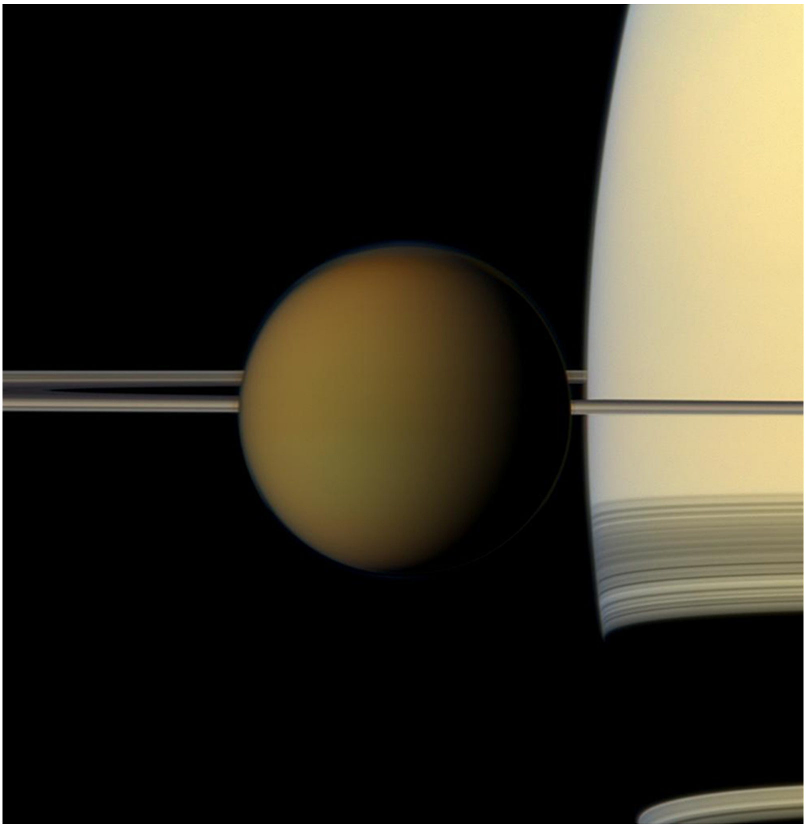

Figure 6.7. Yes, this is a real picture. Titan's surface is concealed by a global haze layer. The rings cast an intricate shadow on Saturn in the background. Image Credit: NASA/JPL/SSI.

One telltale indicator of a liquid surface is the bright specular reflection of sunlight, or 'sunglint', off the smooth liquid surface. This is the kind of reflection one sees on a body of water on the Earth or a bright light reflecting off a mirror or other smooth surface. These reflections proved elusive on Titan because, as it happens, the liquid hydrocarbons are restricted to a handful of lakes near the poles, primarily the north pole, and the relative geometry of the Sun and lake must be the same as the geometry between the lake and Cassini for the glint to be observed. Since Cassini orbits Saturn rather than Titan, the opportunities to observe them were few and far between. An example of a glint, observed in the infrared by Cassini's VIMS instrument at a wavelength where the atmosphere is more transparent, is shown in figure 6.8.

Cassini's RADAR instrument looks at the reflection of long-wavelength radio waves off the surface. These long-wavelength photons pass freely through the hazy atmosphere. Each time Cassini flies by Titan it can point its radio dish at Titan and create an image strip of the surface underneath the spacecraft at radio wavelengths.

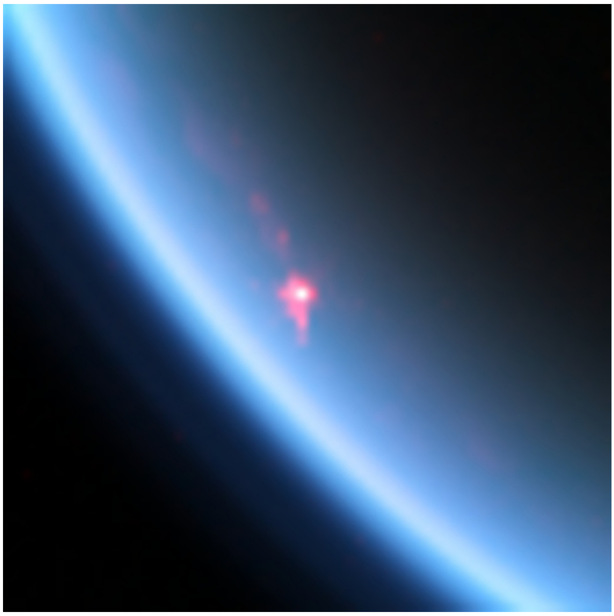

Figure 6.8. This false-color image was taken in the infrared by Cassini's Visual and Infrared Mapping Spectrometer in 2012. The bright point is a reflection off the lake Kivu Lacus near the north pole of Titan. The pink is light from the surface scattering off atmospheric haze layers. The first such specular reflection was observed in 2009 with the beginning of northern spring on Titan so that the Sun could shine on the polar lakes. Image Credit: NASA/JPL/Univ. Arizona.

These images can be deceptive, though. Things that appear bright in a radar image are reflective at the radio wavelengths of a few cm, but would not necessarily appear bright to the human eye. To be reflective of radio waves, the surface must be rough at the scale of the wavelength of the radio waves. Thus, rocky structures like craters, mountains and boulders appear bright, while smooth areas such as plains, deserts and, yes, lakes, appear dark (figure 6.9). Once Cassini started getting radar measurements near the polar regions, well-delineated dark regions with dendritic channels leading into them appeared. While these look for all the world like lakes, it took additional measurements to confirm the case. One particularly dramatic radar observation looked straight down as Cassini flew over one sea on Titan, Ligeia Mare, and measured reflection off the surface of the lake and a separate echo of the radar beam from the lake bottom. This radar observation showed the depth to be up to 160 m (Mastrogiuseppe *et al* 2014). The radar passed through the liquid methane and ethane of the lake and bounced off the bottom. Ligeia Mare (figure 6.9), and presumably the other lakes, are primarily liquid methane based on their radar reflection properties (Le Gall *et al* 2016). The dark appearance of the lakes at radar wavelengths indicates that the lakes are very smooth, with no waves to speak of.

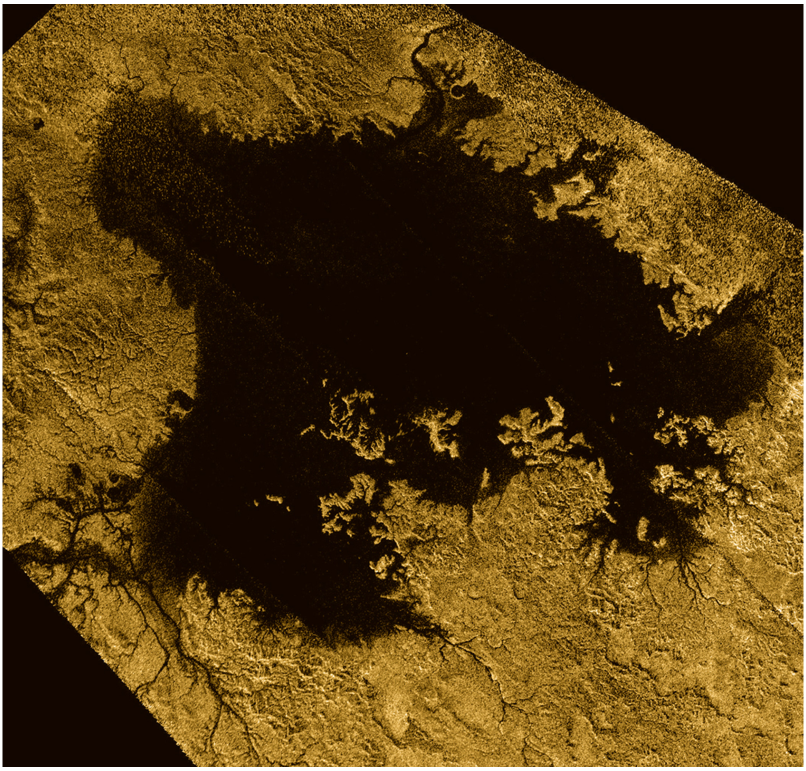

Figure 6.9. This is a colorized segment of a radar image of Titan taken in 2007 by Cassini shows the second largest lake or sea on the moon, Ligeia Mare, in the north polar region. Dark areas are smooth, transparent, or absorbing at the 2 cm wavelength of the radar beam from Cassini. NASA/JPL/ASI/Cornell.

At more equatorial regions, radar swaths revealed sets of nearly parallel linear structures (figure 6.10). These dunes reveal the presence of winds near the surface. Such winds might be expected to produce waves on the lakes, so they may be absent or much weaker at higher latitudes. The largest and most prominent equatorial feature is named Xanadu (figure 6.11). The hydrocarbon-sand dunes lay in the lowlands. Surface winds deflect around higher regions such as Xanadu leaving them rough and bright in radar images. Mountains on Titan are mostly located at equatorial latitudes. The highest mountains are located in Xanadu (figure 6.12).

Even the dry regions of Titan may be playing an essential role in maintaining the lakes and Titan's methane cycle. The processes that break down methane in the upper atmosphere producing ethane, which drifts downward, and hydrogen, which escapes, would empty the atmosphere of its current supply of methane in 10 million years (see Lunine and Atreya 2008 for a detailed description of the methane cycle on Titan). At the same time, Cassini observations don't show much activity in the way of active rainfall or cryovolcanism. The lakes also appear to be relatively stable, so the lakes themselves are not rapidly evaporating to replenish the atmospheric methane (Le Gall *et al* 2016). There must be a source of methane for the atmosphere, or we

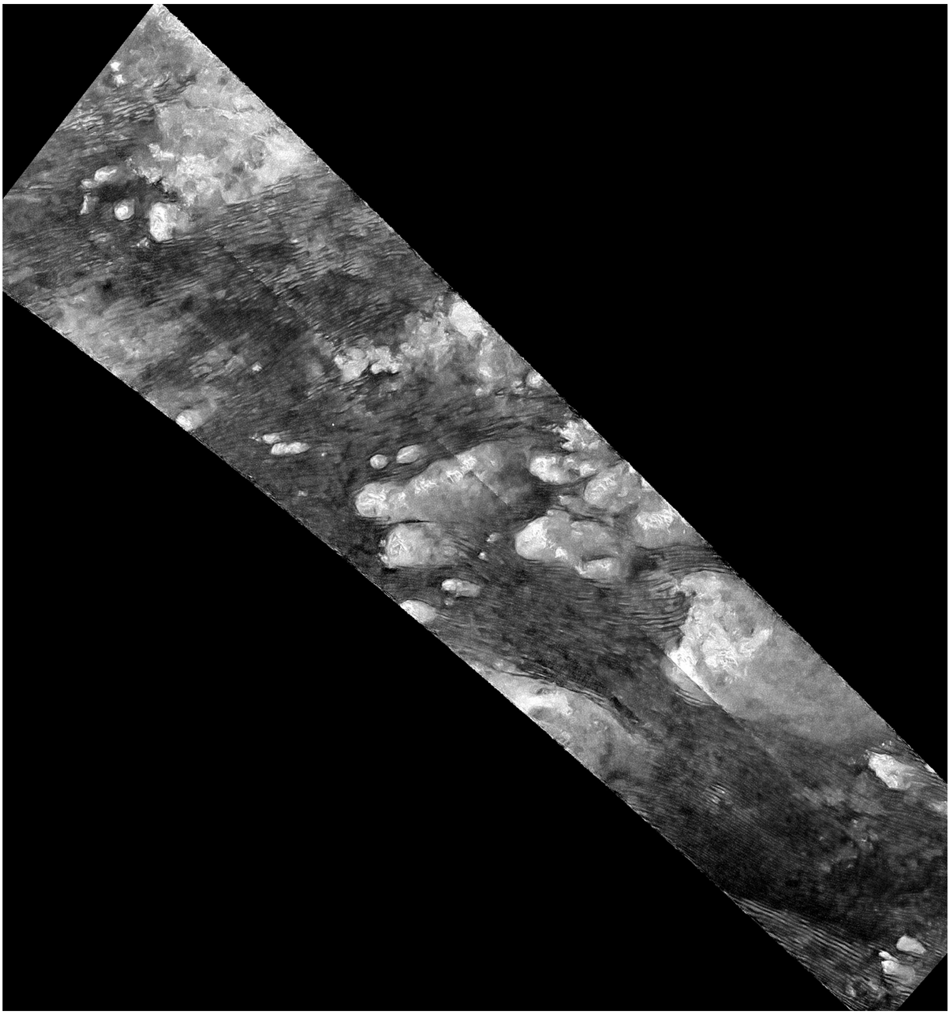

Figure 6.10. This radar image-strip of Titan was taken in 2016 during Cassini's 122 flyby of Titan and shows sets of parallel features that are sand dunes produced by surface winds traveling from west to east (left to right in the image). The dunes are interrupted by mountains and other topographic features that show up as bright regions in radar. Image Credit: NASA/JPL/ASI/Université Paris-Diderot.

are living in a relatively unusual epoch and Titan's current supply of atmospheric methane is due to a recent event that released it from the subsurface. The Huygens probe heated the surface after landing to help boil off volatiles such as methane that could be collected and analyzed by the probe's gas analyzer. The amount of methane measured increased by 40% following this heating (Niemann *et al* 2011).

6.3 Titan's interior

We have seen the dramatic results of tidal flexing in powering the geysers of Enceladus (chapter 4). Titan's orbit is, like Enceladus's, slightly eccentric meaning it

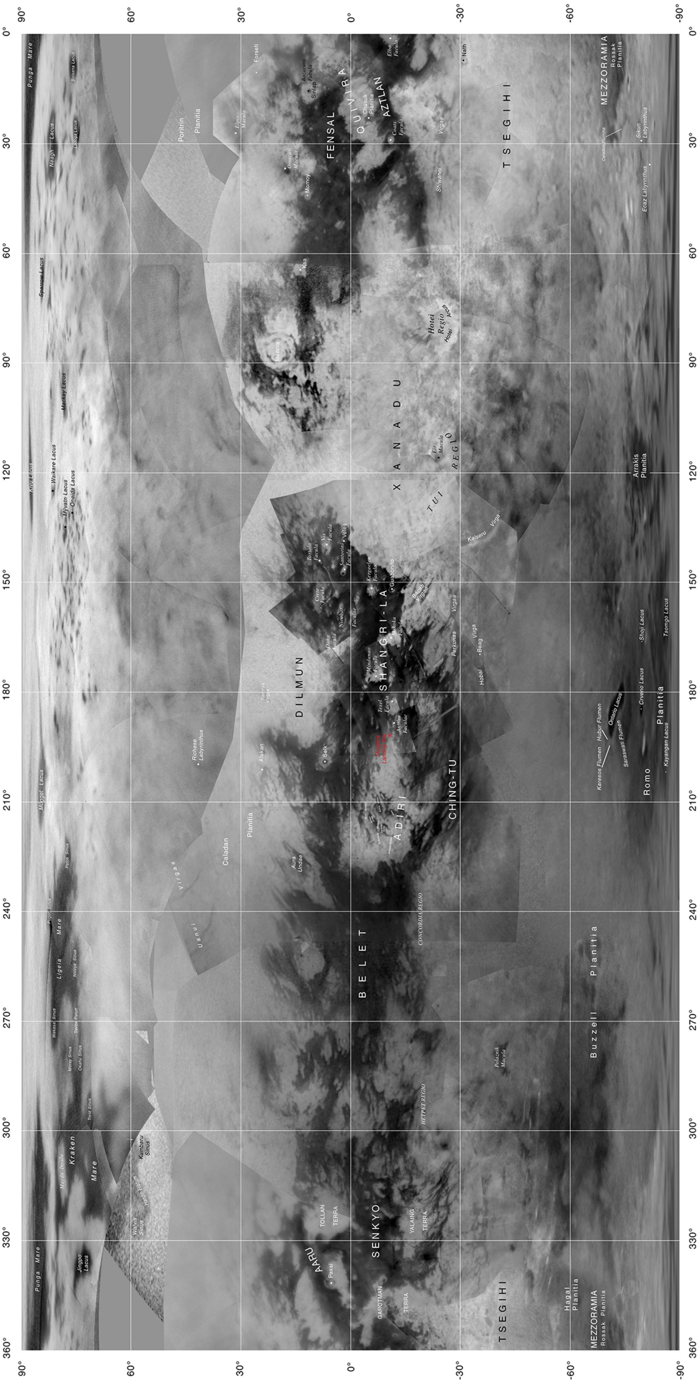

Figure 6.11. This map of Titan is based on a combination of Cassini imaging and radar measurements. The dark equatorial regions are covered in dunes of hydrocarbon sands. The large bright area named Xanadu deflects the winds around it and is sand free. Lakes are found only in the polar regions. Image: NASA/JPL/SSI/USGS.

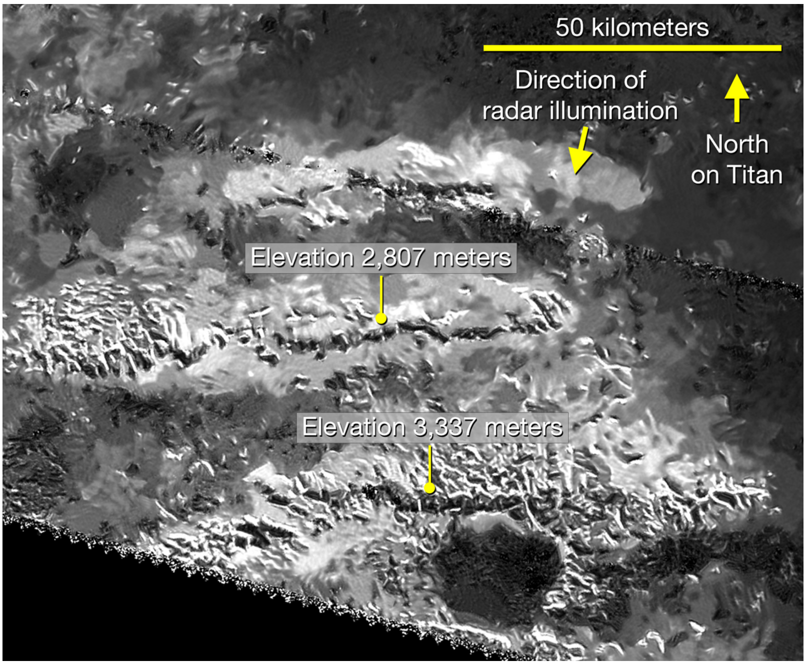

Figure 6.12. These ridges known as Mithrim Montes include the highest mountain peaks on Titan. This is a radar image which shows rough surfaces as bright or reflective, and dark surfaces are smooth or have material properties that allow the radar waves to penetrate rather than reflect off the surface. Image Credit: NASA/JPL.

should have a varying amount of tidal deformation as it orbits Saturn. If Titan were solid through and through, the size of its tidal bulge—the amount of deformation from a mean spherical shape due to the tidal force from Saturn—should be about 1 m. The average ocean tide on the Earth due to the Moon is not much larger than this, and is visible as the sloshing of the oceans up and down our beaches every twelve and a half hours or so. Titan provides no oceans for such measurements, and Cassini lacks the imaging resolution or temporal coverage to see such small changes anyway. Instead, the Cassini Radio Science team was able to measure the amount of tidal flexing of Titan by analyzing the *Doppler shift* of a radio signal from Cassini to the Earth (Mitri 2014, Zebker *et al* 2009).

Just as the siren of a passing ambulance changes tone depending on whether it is approaching or receding from you, the frequency (or equivalently wavelength) of light received from a moving source depends on that source's velocity towards or away from the receiver. The large radio antennas of the Deep Space Network can measure minuscule changes in the velocity of Cassini by monitoring the small changes in its broadcast frequency as its speed is altered by the gravity of nearby objects. This technique is so powerful that by measuring the rate of change of the radio frequency received from Cassini during flybys of Titan at different locations in its elliptical orbit, the radio science team could measure the amplitude of the tidal deformation and found it to be 10 m, 10 times larger than would be expected for a completely solid moon. The only way for such a large deformation to be produced is if Titan's crust is a solid shell disconnected from the bulk of the moon by a liquid layer. Based on the abundance of water ice throughout the Saturnian system, as well as the density profile of the interior of Titan determined from radio Doppler measurements, this global subsurface ocean is almost certainly water.

Just as methane plays the role of water on Titan, water ice plays the role of terrestrial rock. At the low temperatures on Titan, water ice is nearly, but not quite, as hard as rock. The rough terrain on Titan is primarily water ice. Over geologic timescales, these features can relax and deform under their own weight. The tallest mountains on Titan are a little over 3 km in height (figure 6.12), significantly less than the tallest mountains or volcanoes on Earth even though its gravity is much weaker than Earth's. Just as rock is partially molten beneath the Earth's crust, allowing convection that drives plate tectonics and volcanism, water ice is molten in Titan's interior. The presence of large topographic relief, such as the mountains in figure 6.12, in spite of a global subsurface ocean and the generally softer nature of Titan's ice 'rocks' suggests that Titan is geologically active, though the forces driving the mountain building on Titan are probably related to tidal flexing and cooling of the crust rather than the tectonic plate movements and volcanic activity on Earth.

This buried ocean may hold the key to the persistence of methane in the atmosphere. The destruction of methane in the upper atmosphere by solar photons and energetic electrons requires a source at the surface to maintain the current abundance for more than a few million years. Minerals in Titan's interior react with water through a series of reactions called *serpentinization* that produces hydrogen and ultimately methane, where water is the source of the hydrogen and carbon dioxide (CO_2) is the source of the carbon in the methane (Glein 2015). The methane percolates through the crust and into the atmosphere with some eventually finding its way into the polar lakes.

What it must look like to float on a sea of liquid methane, glossy flat, with the faint orange-hued sunlight filtering through the haze high above and a shoreline of ice mixed with hydrocarbons, hard as rock. We must return to Titan with a mobile explorer to sample the wide array of vistas and understand more about how this world works.

Further reading

Following the nominal mission of Cassini and the completion of the Huygens probe mission, a compendium book on results was published that is a companion to the Saturn from Cassini–Huygens book referenced in other chapters: *Titan from Cassini–Huygens,* 2009, Brown R H, Lebreton J-P and Waite J H (ed) Springer. An early look at results from Cassini and Huygens with lots of behind-the-scenes information on the mission is in *Titan Unveiled: Saturn's Mysterious Moon Explored,* 2010, Lorenz R and Mitton J, Princeton University Press.

Cassini at Saturn—Huygens Results, 2007, Harland D M, Springer, provides an overview of the mission and results from Huygens.

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Chapter 7

The Ringed Planet

Our journey through the Saturn system brings us now to the master of the realm, the planet itself. Here we'll see what Saturn is made of and why and how it differs from the other planets in composition and structure. We'll explore the stormy atmosphere, its magnetic field and how it interacts with its family of moons and rings.

7.1 Origin and interior

Saturn, like Jupiter, is a *gas giant* (figure 7.1). The bulk of its mass, which is 95 times the mass of the Earth, is made up of hydrogen and helium. This is not terribly surprising given that those are the most abundant elements in the Universe and also make up the bulk of the Sun. This bulk composition consisting primarily of light gases gives Saturn the lowest density of the planets, just 0.69 g cm^{-3}, less than that of water[1]. Jupiter, with a comparable composition to Saturn, has a much greater density (1.33 g cm^{-3}) because, like Saturn, it is highly compressible: Jupiter's extra mass just compresses the gases more, so while it is more than 3.3 times the mass of Saturn it is only about 19% larger in (equatorial) diameter and 73% larger in volume. The low density and compressible nature of its thick atmosphere, combined with a rapid rotation period of just 10.6 h results in Saturn being the most oblate, or flattened, planet in the solar system. Its polar diameter is just 90% of its equatorial diameter, giving it a noticeably flattened appearance (figure 7.2).

The protostellar nebula was 98% hydrogen and helium, with the remaining 2% mostly comprised of volatile molecules such as water and carbon dioxide, with a small amount of heavier elements and molecules such as metals, SiO_2 (silica), and other minerals. The inner planets of the solar system are composed almost entirely of these less-abundant heavier ingredients of the protoplanetary nebula because close to the Sun the temperatures were too high for anything else to condense into solids.

[1] The density of water is 1 g cm^{-3}.

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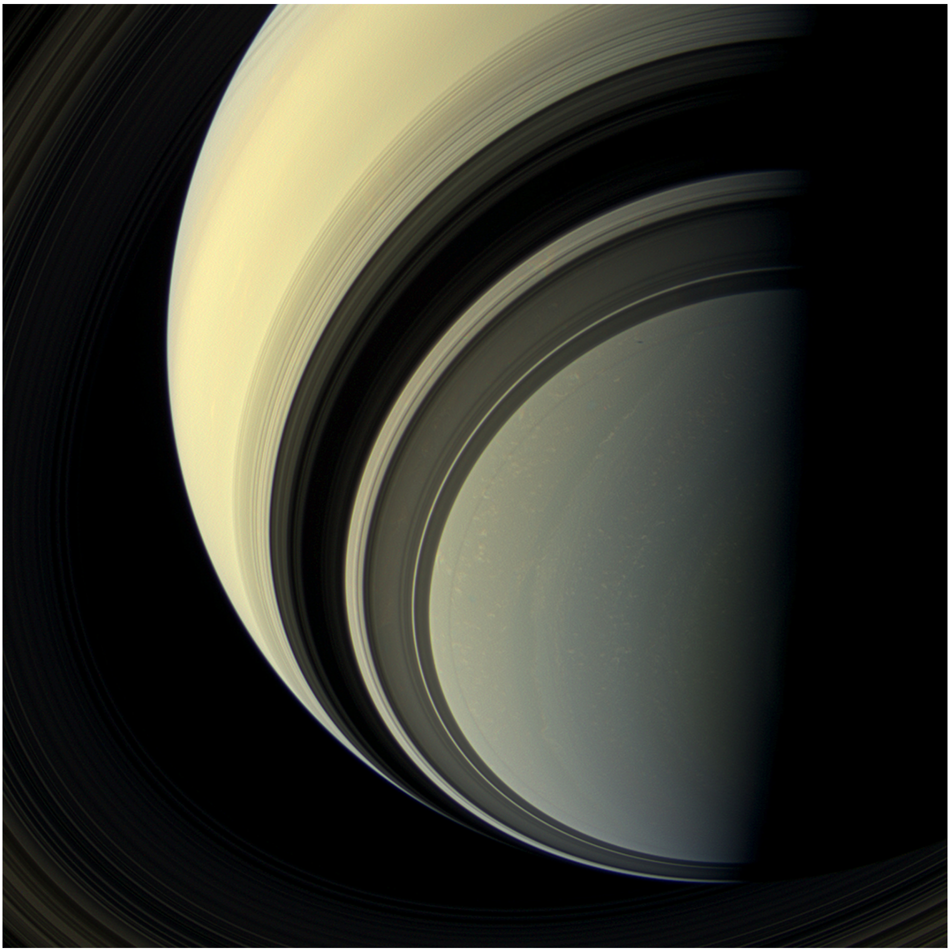

Figure 7.1. This view of Saturn over the south pole, taken by Cassini in northern summer, reveals subtle atmospheric banding and the ever-present shadows of the rings on the planet. Image Credit: NASA/JPL/SSI.

Beyond a few AU[2] from the Sun, however, temperatures were low enough for water to condense from the nebula into solid grains. This greatly increased the amount of solid material available to form planets, leading to larger protoplanetary objects beyond the so-called *ice line*[3].

These larger, icy protoplanets could grow to masses several times that of the Earth, but still much less than the current masses of the gas giants. However, the additional mass provided by ice increased the gravitational pull of these protoplanets enough so

[2] AU stands for Astronomical Unit, and 1 AU is the mean distance of the Earth from the Sun, or about 149 000 000 km.

[3] The precise location of the ice line (also sometimes referred to as the snow line or frost line), where water could condense from the nebula, varied with time as temperatures and pressures in the nebula evolved, but typical numbers would be 2–3 AU.

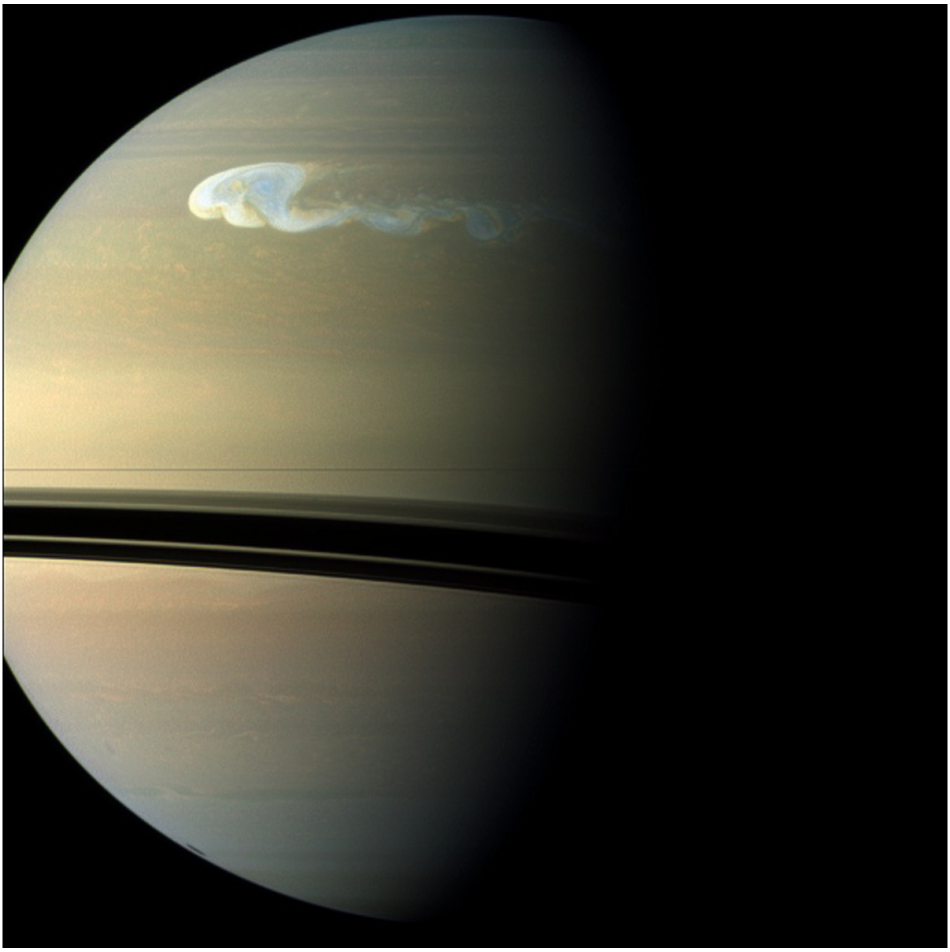

Figure 7.2. This image, in near true-color, shows a large storm in the northern hemisphere. This storm appeared in late 2010 and is seen here on December 24, 2010, about 3 weeks after the first sign of the storm appeared. Over the course of the next few months the storm spread to completely circle the planet. Saturn is noticeably oblate, with an equatorial radius of 60 268 km and a polar radius of 54 364 km. Image Credit: NASA/JPL/SSI.

that they could capture the much more-abundant hydrogen and helium gases (which don't condense at any temperature) from the nebula, dramatically increasing the masses of the planets. The gravitational capture of large amounts of material from the protoplanetary nebula also explains why the outer planets have moons and rings, while the four inner, or terrestrial planets, have a combined total of just three moons and no rings. The captured material formed a miniature solar system, of sorts, with the forming planet, rather than the Sun, at its center.

This gravitational capture was also aided by the lower temperatures in the outer solar system which meant that the hydrogen and helium atoms did not have as much thermal energy. Jupiter, the first planet beyond the ice line, is larger than Saturn (and Uranus and Neptune) because the overall abundance of material available to build planets was largest close to the Sun. Orbital speeds also decrease with increasing distance from the Sun, so the pace of collisions necessary to build planetary cores is also slower further from the Sun. This scenario explains the general architecture of the outer solar system, with Jupiter weighing in at 300 times the mass of the Earth, followed by Saturn at roughly one-third that mass, and Uranus and Neptune further out and another factor of four less-massive. It is worth noting, however, that hundreds of planetary systems discovered around other stars do not follow this pattern. Migration of planets after they form seems to have played a greater role in shaping the final planetary configuration than it may have in our own, though the 'Nice model' discussed in chapter 3 does involve significant reshuffling of the outer planets some 3.8–3.9 billion years ago. The architecture of our solar system may not be typical, if there even is such a thing as a typical planetary system.

Saturn, like all the planets and large moons, is *differentiated*: the densest material has settled to the center or core of the planet, with the least-dense elements in the outer layers. In the case of Saturn and the other outer planets, the core is dominated by the most abundant compound that could condense beyond the ice line (namely, ice) with significant fractions of rocky compounds mixed in. The precise amount of material in Saturn's core is not known, but is likely about 10 times the mass of the Earth (Guillot *et al* 2009). This core may extend out to about 1/3 of the radius of the planet.

Differentiation is still occurring deep in the interior of Saturn as helium rains out of the primordial mixture of hydrogen and helium gases. This helium rain settles into a layer of helium and so-called *metallic hydrogen* that surrounds the core of rock and ice. Metallic hydrogen can form when the pressures on hydrogen are millions of times the atmospheric pressure at the surface of the Earth (Dias and Silvera 2017). The enormous mass of Saturn is able to produce such pressures deep in its interior. When the helium atoms fall toward the center, they produce heat as their gravitational potential energy is lost when they land[4]. This ongoing process of differentiation explains why Saturn radiates roughly twice as much energy as it receives from the Sun.

Above the metallic hydrogen layer there is a thicker layer of liquid hydrogen which can be produced on the Earth at very low temperatures and is used as a rocket propellant[5]. Most of the mass of Saturn, some 99.9%, is thus in a solid or liquid state even though we refer to it as a gas giant. That is because the bulk of the material in the planet is hydrogen and helium, and these are gaseous under normal (terrestrial) pressures and temperatures. There is considerable uncertainty about the internal structure of Saturn. One way to learn about that internal structure is to study the gravitational field of the planet. Different distributions of mass within the planet produce small differences in the orbits of objects around it. The different orbital

[4] The term 'land' here is colloquial. This takes place deep in the interior of the planet where the pressures are crushingly high. The helium 'rain' is drifting slowly through dense liquid hydrogen until it meets the even denser layer of metallic hydrogen. Sediment falling slowly through water is a closer analogy.

[5] The Centaur upper stage of the rocket that launched Cassini burned liquid hydrogen with liquid oxygen, producing water as exhaust.

periods (azimuthal, vertical and radial) that give rise to the waves in the rings discussed in chapter 5 are a result of a non-spherical distribution of matter in the planet. Thus, measuring at very high precision the motion of an object moving under the influence of Saturn's gravity alone, combined with our understanding of the physics of how different materials compress under different pressures, constrains the internal structure of the planet. Cassini is just such an object, and by tracking the frequency of its radio signal we can measure the how Saturn's gravity affects the motion of the spacecraft as it flies through the system. The most sensitive measurements will come at the very end of Cassini's mission, in the summer of 2017, when it passes between the rings and the planet.

7.2 Atmosphere

Saturn's atmosphere at altitudes above the pressure at the surface of the Earth (1 bar) behaves in general like that of Titan (chapter 6): the top is heated by the Sun and impacting charged particles, and the bottom is heated by the planet. In the case of Titan the heating from below comes from the surface of Titan. Saturn does not have a surface, per se, but as discussed above, heat is radiating outward from its interior, likely due to the rain out of helium deep in its interior[6]. Thus, like Titan (and the Earth), Saturn has a troposphere where convection produces clouds, and a warm *thermosphere*, heated by energetic solar photons and charged particles, where the atmosphere thins into the emptiness of space.

The rapid rotation of such a large planet means that the clouds generally stretch around the planet in latitudinal *zones*. In general, there is more heating over the equator causing air to expand and rise. At the top of the troposphere it is pushed aside by more rising warm air beneath, so it moves north and south where it cools and sinks, displacing air at the surface. Thus there is a circulation pattern of rising and sinking air, with air rising at the equator, and sinking at a more northern (or southern) latitude. As the air rises and cools, any molecules that can condense form clouds, which can produce rain. The sinking air is depleted of this moisture and is thus dry. This circulation pattern produces *Hadley cells*, and the number of Hadley cells that fit between the equator and the pole is determined by the size of the planet and the speed of rotation. On Earth, that number is three and explains why it is rainy over the equator and at mid-latitudes while deserts occur where the first Hadley cell sinks (at the latitude of the Sahara, for example).

These zones of rising and sinking air give Jupiter its prominent striped appearance, where the regions of rising air produce bright, reflective clouds at the top of the troposphere, and the neighboring regions are clear and allow us to see to deeper levels in the atmosphere where there are reddish and yellow sulfur-bearing clouds. Saturn has less dramatic color contrasts (figure 7.3) because the atmosphere is more vertically extended than Jupiter's due to its smaller mass and therefore weaker gravitational compression of the atmosphere under its own weight[7]. With a thicker

[6] This process has been going on for 4.5 billion years!

[7] For the same reason we saw in chapter 6 that Titan's atmosphere is much more vertically extended than the Earth's.

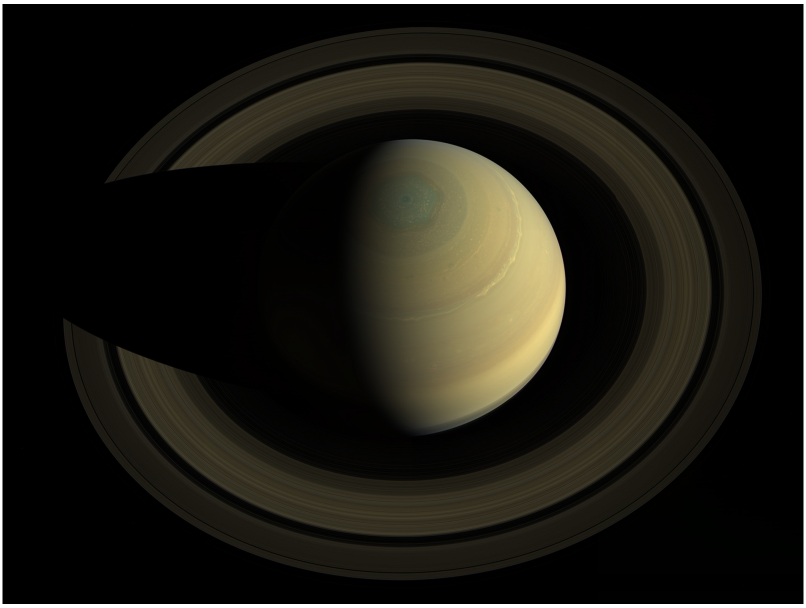

Figure 7.3. This true-color view of Saturn from high above the north pole is a mosaic of 36 Cassini images from 2013. A thin band of white clouds at 42° north latitude is leftover from a major storm that peaked in 2011 (see figure 7.2). The north pole is sunlit at this time and is circled by a hexagonal feature. Image credit: NASA/JPL/SSI.

atmosphere, haze makes it harder to see down to the levels where the darker clouds reside. Saturn has three main cloud levels: ammonia clouds at an atmospheric pressure of 1 bar, ammonium hydrosulfide at a few bars, and water clouds at about 10 bars (1 bar is the atmospheric pressure at sea level on Earth)[8]. The water clouds are too deep to be visible, normally. Occasionally, however, Saturn's relatively uniform atmospheric appearance is interrupted in dramatic fashion by the eruption of a storm which gradually circles the planet. One such storm appeared during Cassini's mission, in 2010 (figure 7.2), but they have been observed from Earth-based telescopes for over a century (Li and Ingersoll 2015). It is a coincidence that the appearance of these global storms roughly coincides with the length of Saturn's year, or about 30 years.

On Earth, storms are launched by contrasts in heating of the atmosphere at the surface due to different surface temperatures (warm land next to cool bodies of water, for example, or even warm asphalt and concrete next to cooler vegetation) or the flow of the atmosphere over topography, such as hills and valleys. Saturn has no such obvious sources of uneven heating to drive the generation of storms, so it is not surprising that in general Saturn's cloud cover is much more constant and uniform than that of the Earth (figure 7.3). And yet, storms do sometimes crop up on Saturn,

[8] See Del Genio *et al* (2009) and references therein for details on Saturn's atmosphere discussed in this chapter.

and grow to circle the planet. The energy source for Saturn's storm is heat liberated from the interior through differentiation discussed above.

The same processes that give rise to hurricanes on Earth act on Saturn. As rising air moves northward or southward, it is deflected east or west by the *Coriolis force*. Here's why. A 'parcel' of air at Saturn's equator is moving around the center of Saturn at about 36 000 km h^{-1} because it has to go around the full circumference of the planet in a Saturn day (10.55 h). A parcel of air near the north pole, on the other hand, has a much smaller journey to make in a Saturn day because it is close to the rotation axis, and it is therefore traveling much slower (about 25 000 km h^{-1} at 45° latitude). So an air parcel moving northward from the equator is like a car moving from the fast lane into the slow lane: suddenly it is moving much more quickly than its neighbors, while an air parcel moving toward the equator from the north is like a slow car moving into the fast lane. This results in a circulation of the air around local highs or lows in the atmospheric pressure (figure 7.4).

Saturn has a yellowish hue due to absorption of red light by methane and other trace molecules in the atmosphere and an upper-atmospheric haze of suspended particles that obscure our view of clouds below. The longer a path that sunlight takes through the atmosphere, the more red light is absorbed and the bluer that atmosphere appears (figure 7.5). This gives the winter hemisphere a bluish tint compared to the summer hemisphere. Another seasonal change in the atmosphere that is unique to Saturn is the large shadow that the rings cast on the planet (figure 7.6). However, its effect on Saturn's weather is probably small: as we saw for Titan in chapter 6, Saturn's great distance from the Sun and hazy atmosphere reduce

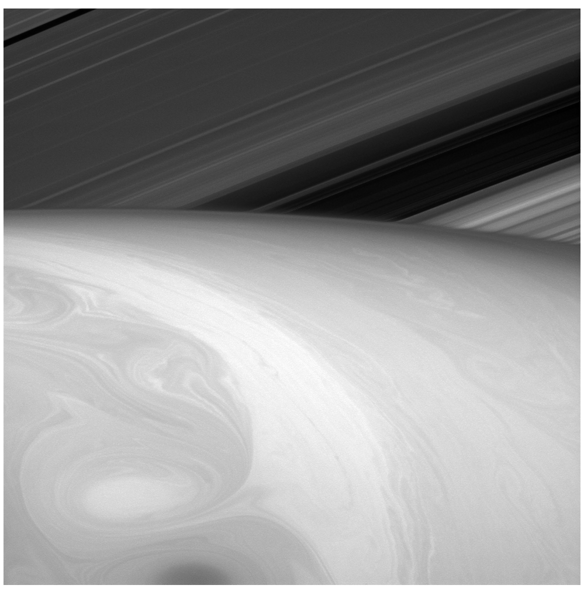

Figure 7.4. Clouds are emphasized in this view taken by Cassini in 2014 through a red filter illustrating the complicated fluid dynamics present in a rapidly rotating atmosphere. The resolution is about 100 km $pixel^{-1}$ of this view of northern mid-latitudes. Image Credit: NASA/JPL/SSI.

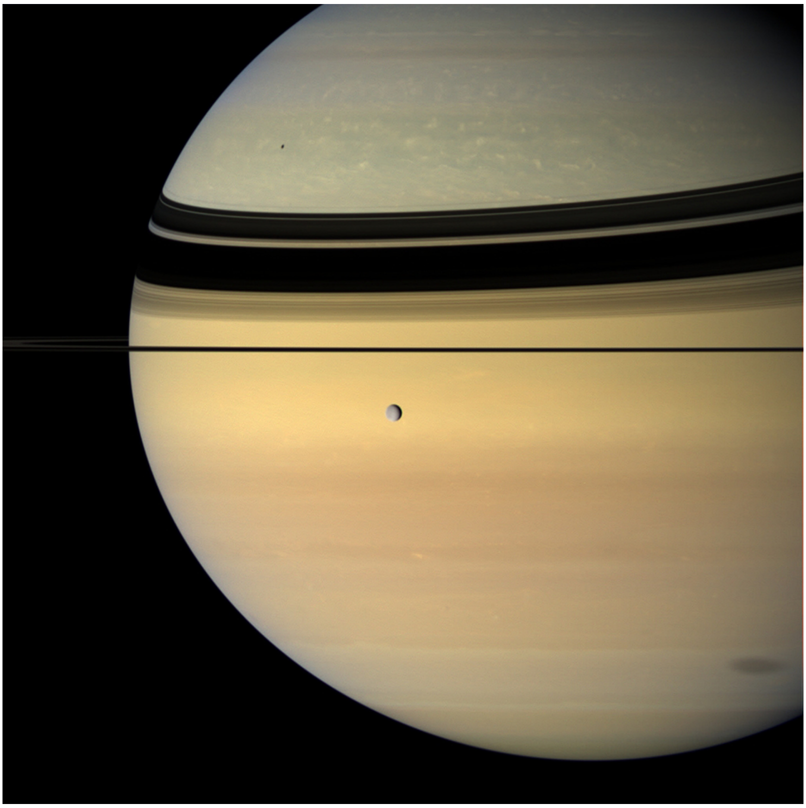

Figure 7.5. This true-color image from the equatorial plane of Saturn shows the yellower hue of the atmosphere in the Sunlit southern hemisphere and bluer tones in the wintry northern hemisphere. The gases in the atmosphere preferentially absorb red light, so the more air that sunlight passes through before being reflected back to Cassini's cameras the bluer it appears. The Sun is shining on the planet's southern hemisphere, so sunlight hits the northern atmosphere at an oblique angle, passing through more air before it is reflected off clouds. Image Credit: NASA/JPL/SSI.

the amount of solar energy reaching deep into the atmosphere, and this diminishes the effects of seasonal fluctuations to the upper atmosphere.

As with Titan, we can see to different depths in Saturn's atmosphere by observing at different wavelengths of light. Unlike Titan, however, there is no solid surface to observe beneath the atmosphere. Heat from Saturn's interior, however, produces a glow in the infrared part of the spectrum that can act as a backlight to illuminate clouds that would otherwise be obscured by haze from above (figure 7.7). By combining observations from Cassini's cameras we're able to piece together the structure of the atmosphere.

A curious feature of Saturn's northern polar region is a hexagonal feature in the clouds (figure 7.8). This feature was observed in Voyager images (Godfrey 1988, Del Genio *et al* 2009) and has remained stable since that time and may be much older. While it may seem odd to see an angular structure in the atmosphere of a spherical

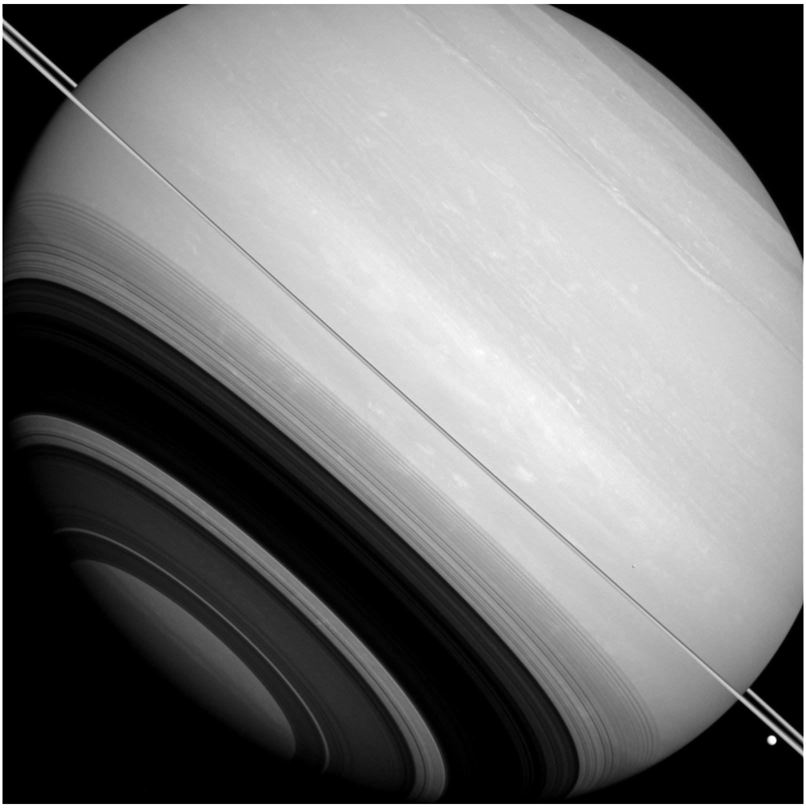

Figure 7.6. This image taken from Saturn's equatorial plane shows the dramatic difference in sunlight hitting the two hemispheres due to the shadow of the rings. In this view the Sun is high above the ring plane so the rings cast a broad shadow over the southern hemisphere. The shadow moves from the south to the north and back again over the course of a Saturn year, vanishing to a thin line at the equinoxes when the Sun shines on the rings edge-on. Image Credit: NASA/JPL/SSI.

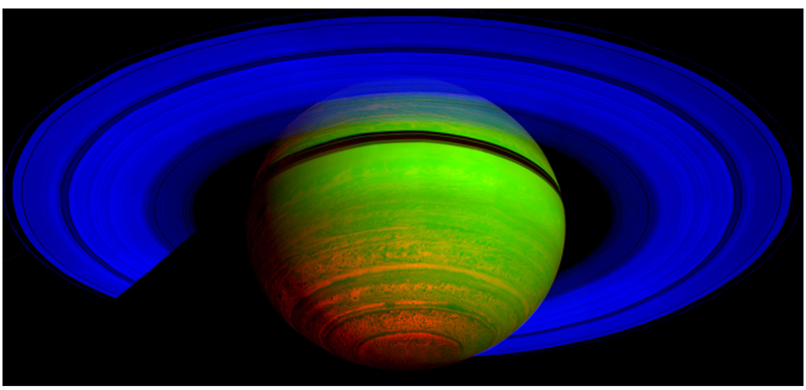

Figure 7.7. This false-color view of Saturn and its rings was produced from images taken with the Visual and Infrared Mapping Spectrometer in three different infrared wavelengths. Blue and green are reflected sunlight, while the red indicates the glow from Saturn's interior. Clouds in the southern hemisphere are seen in silhouette in front of this intrinsic glow. Image Credit: NASA/JPL/Univ. Arizona.

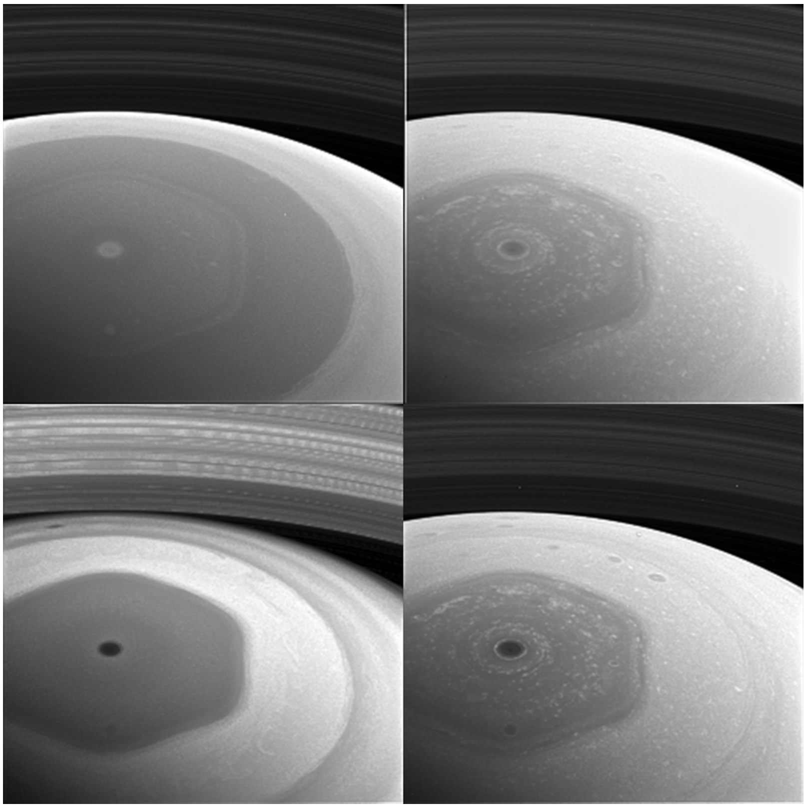

Figure 7.8. These four views of the north polar region reveal the hexagon at different wavelengths of light (from upper left, clockwise, the colors go from violet to infrared) and therefore different depths in the atmosphere. The hexagon and clouds associated with it are most prominent in the red and infrared which also reveal a dark spot at the pole indicating a cloud-free zone. Image Credit: NASA/JPL/SSI.

planet, the hexagonal appearance is a bit misleading. If we superimpose a circle on the hexagon and then unwrap it, we see that it is actually a sinusoidal wave wrapped around the planet (figure 7.9). This by itself does not explain the origin of the hexagonal feature, but makes its shape somewhat less confounding. There is a 'north polar spot'—a local storm—adjacent to one side of the hexagon that may be involved in its formation by diverting a zonal flow (like a terrestrial trade wind) around it (Allison *et al* 1990), or its roots may go deeper into the planet (Barbosa Aguiar *et al* 2009). In either event, the south pole does not have a matching feature (figure 7.10). The north pole itself is the location of a hurricane-like circulation with high cloud walls reminiscent of the eye-wall of a hurricane (figure 7.11).

The atmospheric winds can be measured by looking at sequences of images and identifying small features and tracking them from frame to frame (figure 7.12). This provides the speed that the air is moving in an absolute sense, but to convert that to wind speeds we have to know how fast Saturn itself is rotating. When talking about a gas giant planet like Saturn, though, it's sometimes difficult to know what is even

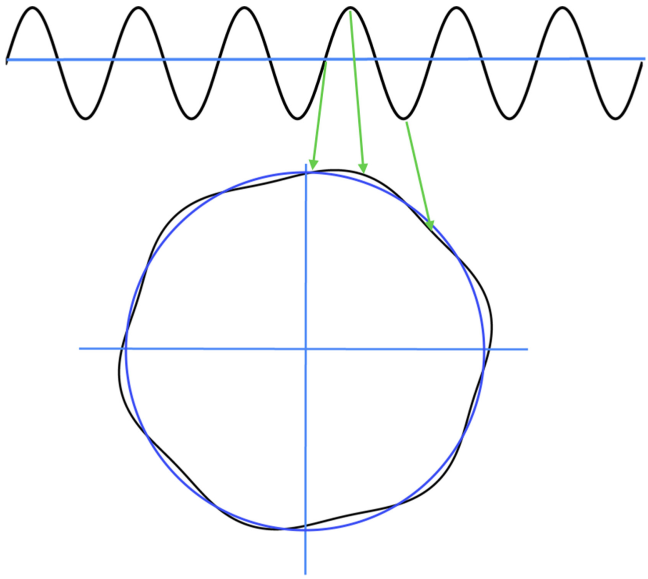

Figure 7.9. This schematic illustrates how a traveling sinusoidal wave (top) can become a hexagon when it is wrapped around a circle with a periodicity of six wavelengths around the planet.

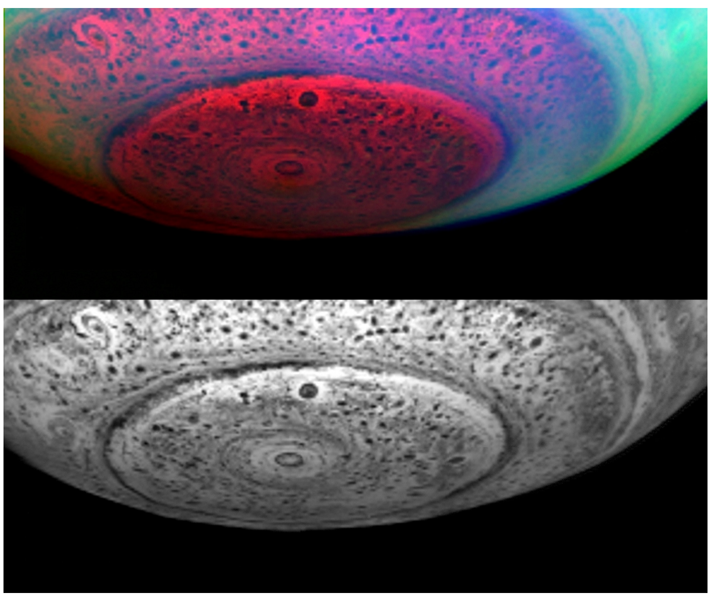

Figure 7.10. These two views of the south pole show circular air flows around the pole, but no hexagonal feature like that seen at the north pole. Both images were taken in the infrared with the Cassini VIMS instrument. The lower panel is at 5.04 microns where clouds appear dark silhouetted against the thermal emission from the interior of the planet. The lower image makes up the red part of the upper false-color image where green and blue represent reflected sunlight at 4.08 and 3.08 microns, respectively. The redder appearance of the polar region indicates that it is relatively clear of the high altitude hazes that reflect sunlight at more equatorial latitudes. Image Credit: NASA/JPL/University of Arizona.

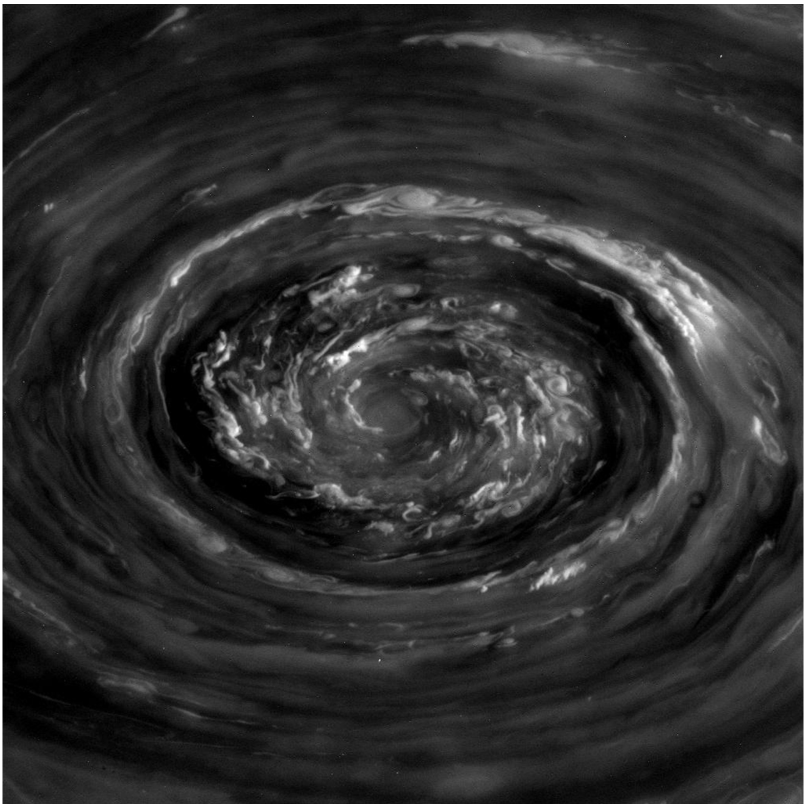

Figure 7.11. This dramatic image shows the circulation around the north pole of Saturn. Image Credit: NASA/JPL/SSI.

meant by 'Saturn itself'. The parts that we see—the clouds and various waves and disturbances in the atmosphere—are all moving, and their speeds with respect to the center of the planet are all different, varying primarily with latitude. We can't see a surface to provide a reference frame for the wind speeds, so we have to turn to other observations to infer the rotation rate of the bulk of the planet. This is where the magnetic field comes in handy. The rate that we get for the rotation of the planet suggests that most of the atmosphere is super-rotating (winds blowing toward the East, in the same direction the planet is rotating) at speeds up to several hundred miles per hour at the equator.

7.3 Magnetic field

Like the Earth, Saturn has a magnetic field that to a first approximation is like that of a bar magnet. But while the Earth's magnetic field is tilted by a few degrees from the rotation axis, Saturn's is nearly perfectly aligned with it: its north magnetic pole is in the same direction as its north rotational pole (see chapter 4, figure 4.9). However, it is asymmetric about Saturn's equator as if the bar magnet were

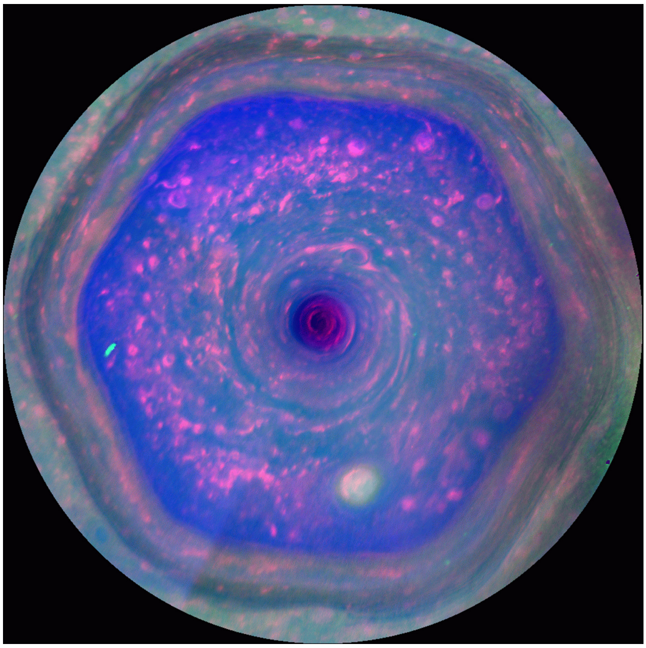

Figure 7.12. This false-color mosaic of Saturn's north pole shows the hexagon, the north polar white spot, and the polar storm. This time lapse covers 10 h or about one full rotation of Saturn and is in a frame rotating with Saturn so all motions here are due to atmospheric winds. The air in the hexagon is like a jet stream that prevents air from crossing it. Movie Credit: NASA/JPL/SSI/Hampton University.

displaced slightly to the north. Planetary magnetic fields are generated by a form of *dynamo* in the interior of the planet. Electrical currents generate magnetic fields, so a planetary dynamo involves some bulk circulation of conducting material in a planet's interior. In the Earth this is likely due to convection in the outer core of heavy metallic elements. At Saturn the field is generated in the metallic hydrogen envelope outside the core. The precise mechanisms for generating the field and the nature of the flows in the interior are both complex and incompletely understood. The north–south asymmetry in Saturn's magnetic field (and the tilts in those of Earth and Jupiter, for example) show that the generation of the field is not simply connected to rotation at the core of the planet. Cassini's final orbits will provide valuable new constraints on both the magnetic field and the structure of the interior of the planet. The magnetic field at the cloudtops of Saturn is comparable in strength to that at the surface of the Earth. However, since Saturn is roughly ten times larger than the Earth, the total magnetic field density at Saturn is nearly 1000 times larger than that of the Earth (Gombosi *et al* 2009).

Charged particles tied to the magnetic field can radiate at radio wavelengths, so any periodicity to these emissions is tied to the rotation of the magnetic field. At Jupiter, the tilt of the magnetic field from the rotation axis of the planet makes these radio emissions stand out like the beacon from a lighthouse. At Saturn, though the field is aligned, there is still a periodic signal in radio waves called *Saturn Kilometric*

Radiation (SKR). Following the first measurements of SKR it was thought that, like at Jupiter, the period of the fluctuations in this signal indicate the period of rotation of the bulk of the planet. However, the period of the SKR has changed since the Voyager epoch, and it's not possible for the bulk rotation of the planet to have changed that much so quickly. Even more curious, the period of the SKR split during the Cassini mission indicating different emissions from the northern and southern hemispheres of Saturn (figure 7.13). This strange behavior of the SKR at Saturn is not fully understood, but its changing and bimodal nature means that it is not governed entirely by magnetic field generation deep within the planet. There is some modification of the emission that arises in the atmosphere of Saturn, or at least less-deep in the interior, that can undergo changes on timescales of years.

We have another clue to the internal structure and period of the planet from Saturn's rings. As we saw in chapter 5, the rings are a dynamically quiet system that is very sensitive to even very weak perturbations, such as the gentle gravitational resonant tugs on the particles from nearby small moons. Any mass that has a motion with a period that is resonant with one of the natural frequencies of ring particles can launch a wave at the location in the rings where that resonance occurs (chapter 5). Voyager data showed a handful of unusual waves in the C ring, and Cassini data revealed many more. These waves do not correspond to any resonances with known moons, and in some instances seem to propagate in a direction that indicates they are caused by a perturber interior to them, rather than outside the rings as with the rest of the known waves. It was recognized that these may be caused by natural

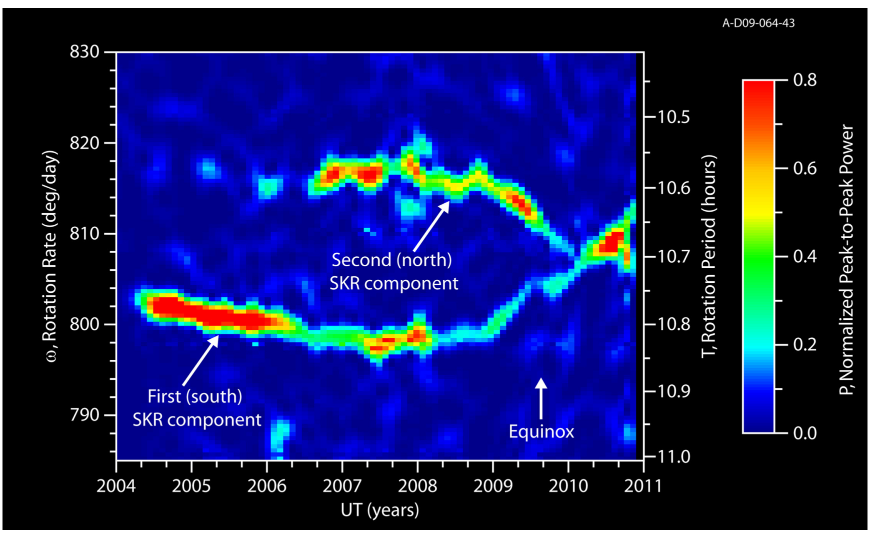

Figure 7.13. This figure is a spectrogram where time is on the horizontal axis and the frequency of the Saturn Kilometric Radiation is plotted vertically. Colors indicate the intensity of the radio emission at each frequency. SKR emission was used to determine the rotation period (length of day) of Saturn until it was seen to change, and then a second component appeared. Observations made since this observation show a merging of the two components (Fischer *et al* 2015) followed by a separation with the north component slower than the south (Ye *et al* 2016). Image Credit: NASA/JPL/University of Iowa.

oscillations within Saturn itself (Marley and Porco 1993), and the abundance and quality of measurements made by Cassini has confirmed this to be the case. The rings are ringing, for lack of a better word, in resonance with bulk oscillations within the planet or the motion of some asymmetric distribution of matter in the planet, or both (Hedman and Nicholson 2014).

The magnetic field is a barrier to the charged particles streaming out from the Sun in the solar wind. Some of these electrons and protons become trapped by the magnetic field. As discussed in chapter 4, these particles spiral along the magnetic field lines. Depending on the energy of the particles and their location within the magnetic field, they can impact Saturn's atmosphere creating aurorae, the same process that produces the aurorae on Earth. When electrons hit molecules in Saturn's upper atmosphere (mostly molecular hydrogen), they can cause those molecules to glow. The emission from hydrogen is primarily in the ultraviolet, so we typically don't see the aurorae in our visible light images. It is quite prominent in the ultraviolet images taken by Cassini's Ultraviolet Imaging Spectrograph (UVIS, figure 7.14) and also by the Hubble Space Telescope. Visible light images of the aurorae have been captured looking at the nightside of the planet. Saturn's vertically extended atmosphere, a product of its low overall density, means that the electrons interact with atmospheric hydrogen over a large vertical extent producing auroral 'curtains' that are the tallest in the solar system (figure 7.15).

In addition to the solar wind, two of Saturn's moons make significant contributions to the population of charged particles in the magnetosphere. As we saw in chapter 6, methane in the upper atmosphere of Titan is destroyed by sunlight and the solar wind producing hydrogen that escapes into space, becoming part of the

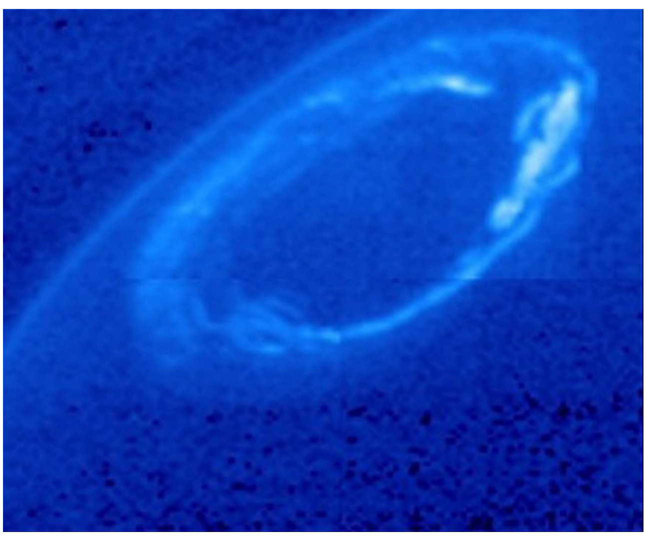

Figure 7.14. Ultraviolet movie of Saturn's north polar aurora from the Cassini UVIS and the Hubble Space Telescope. The intensity and configuration of the aurorae change with the strength of the solar wind. Movie Credit: NASA/JPL-Caltech/University of Colorado/Central Arizona College and NASA/ESA/University of Leicester and NASA/JPL-Caltech/University of Arizona/Lancaster University.

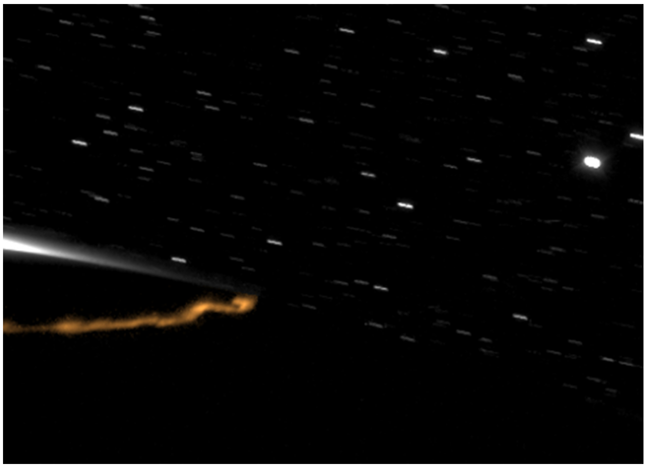

Figure 7.15. This animation shows Saturn's northern aurorae in visible light. The timelapse spans 81 h and shows aurorae in false color extending up to 1200 km above the visible edge of the planet. The glow at the left is scattered sunlight from the upper atmosphere on the dayside of the planet. Movie Credit: NASA/JPL/SSI.

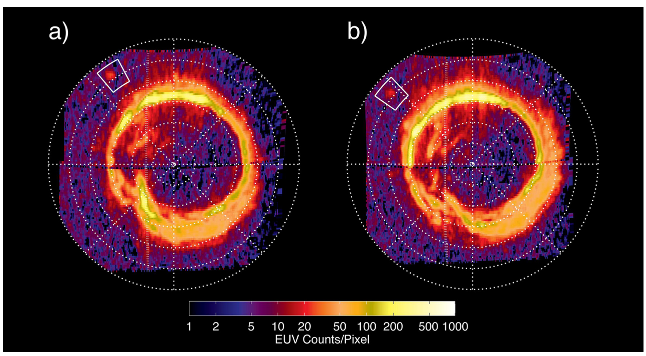

Figure 7.16. These Cassini UVIS images show Saturn's aurorae and a spot of emission that maps directly to Enceladus (boxes). Image Credit: NASA/JPL/Univ. Colorado/Central Arizona College.

magnetosphere. Meanwhile the geysers of Enceladus launch water molecules directly into the magnetosphere, and water is dissociated into hydrogen and oxygen by energetic solar photons. Some of these atoms become ionized, but there is also a large population of neutral atoms in Saturn's magnetosphere from these two sources. Electrons produced by ionization of the water vapor from Enceladus can precipitate directly along the magnetic field lines that pass by Enceladus and impact Saturn's atmosphere. The Cassini UVIS has observed a spot in the aurora that corresponds to the field lines that pass by Enceladus, directly demonstrating this link (figure 7.16) (Pryor *et al* 2011). However, the spot appears only occasionally, and the origin of this fluctuation is uncertain. Enceladus' water vapor production appears to have remained fairly constant over the course of the Cassini mission, but only a few direct measurements of this output have been made (Hansen *et al* 2017) so temporary increases in activity cannot be ruled out.

Many of the atoms and molecules fed into the magnetosphere by Titan and Enceladus remain un-ionized, giving Saturn large belts of neutral gas in the magnetosphere, a characteristic that is unique to Saturn in the solar system. Saturn's interior, both deep within the planet where the rain-out of helium provides an internal heat source and at shallower levels where inhomogeneities may launch waves in the rings and slippage between the outer and inner layers of the planet alters the SKR, remains a mystery wrapped in tens of Earth masses of hydrogen and helium. Cassini's final orbits will provide the best measurements of the magnetic and gravitational fields as well as continued measurements of the rings at high resolution and the SKR. These data will help us better understand how Saturn formed and evolved.

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Chapter 8

Future exploration of the Saturn system

The Cassini mission's exploration of the Saturn system has spanned more than 13 years, making Saturn the most comprehensively studied planet in the solar system after the Earth and Mars. Exploration of Jupiter by the Galileo mission, a scientific sibling to Cassini in many ways, was hampered by the failure of its high gain radio antenna to deploy, greatly reducing the amount of data it could transmit to Earth. Jupiter is far from neglected, however, with the Juno mission exploring its interior as a model of Cassini's Grand Finale orbits at Saturn. NASA's plans for exploration of the outer solar system are focused on 'ocean worlds' and astrobiology, and is currently planning a Jupiter orbiter that will be focused on detailed studies of Europa, an icy moon with a subsurface ocean of its own.

Cassini has provided clear evidence that both Enceladus and Titan are ocean worlds. Enceladus' ocean may be much closer to the surface than Titan's or Europa's, and in any event, unlike those moons, it provides us free samples of the ocean by spitting water vapor and ice crystals out into space. A focused mission to Enceladus could analyze these ocean samples in much greater detail than Cassini's instruments. If the ingredients for life are present, such a mission could find them.

While Titan's sub-surface ocean[1] is not accessible, Titan itself would be a planet in its own right if it were in orbit around the Sun. Cassini's cameras and radar have done much to reveal Titan's surface, Doppler tracking has shown us much about the interior structure, and the Huygens lander provided a tantalizing and detailed glimpse at one moment in time and one spot on this world (figure 8.1). But there are lakes, vast fields of sand dunes, mountain ranges, and a weather cycle whose daily and seasonal patterns remain incompletely understood. Fortunately, Titan does provide an atmosphere that would enable global exploration via balloon or airship. That is a mission I would love to see.

[1] Not to be confused with its large lakes of liquid methane and ethane on the surface, which are ripe for exploration.

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Figure 8.1. The Huygens probe operated on the surface of Titan after landing. This is its view of the horizon. The rocks in the foreground are likely made of water ice and are about 10 cm across. Image Credit: ESA/NASA.

The end of the Cassini mission features the highest-resolution images of the rings, and it will take a dedicated mission to the rings themselves with a spacecraft that tracks along with the ring particles to improve on these and show us individual particles. Nevertheless, the end-of-mission images are already stunning (figure 8.2).

We have seen objects down to the resolution limit of the Cassini cameras, both within the rings and among the moons. The F ring has shown us accretion and fragmentation processes playing out before our eyes at the boundary of Saturn's Roche zone. This provides a tantalizing link to suggestions that many of the moons in the system may be young, either fragments of larger objects or perhaps born from the outer edge of the rings themselves. The conclusion of the mission will not immediately resolve the questions of the age and origin of the rings and moons—science takes time to get things right—but the data collected over the course of the

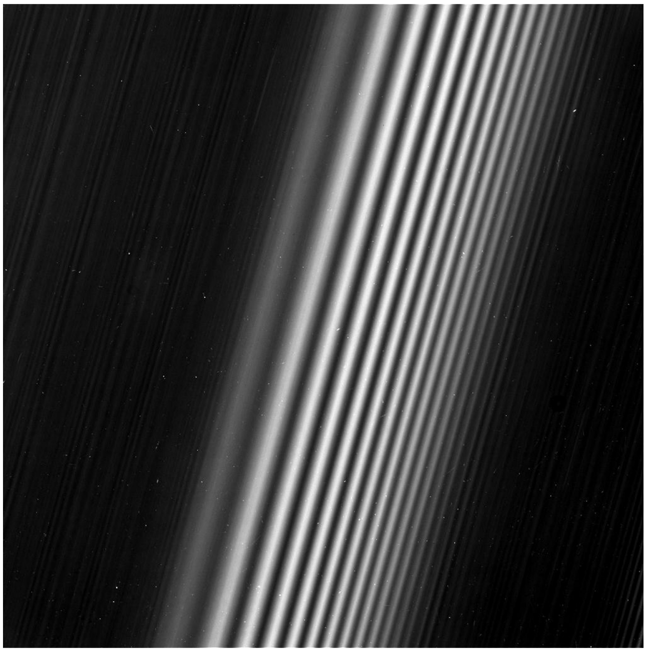


Figure 8.2. This image from the start of Cassini's final mission phase shows the Mimas 5:3 bending wave (see also chapter 5). The planet is to the right. Image Credit: NASA/JPL/SSI.

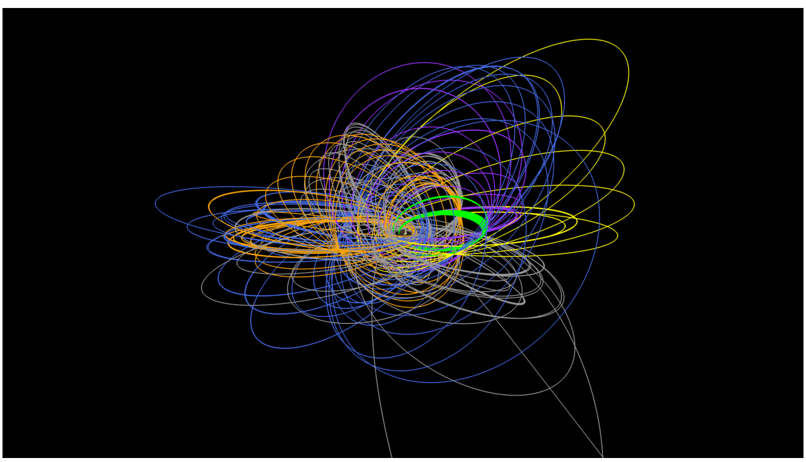
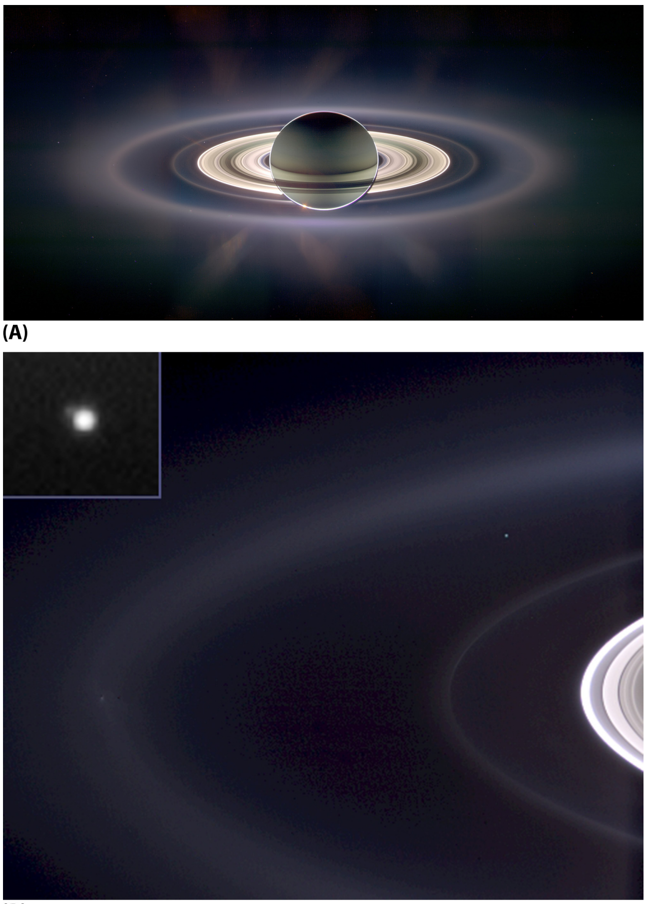


Figure 8.3. This computer rendition shows the entire Cassini 'tour' of the Saturn system. Saturn is too small to see, at the center of the action. The colors indicate the phase of the mission, ranging from gray for the initial 4-year prime mission to the final orbits in green. Movie Credit: NASA/JPL.

mission has already rewritten our understanding of the history of Saturn. In its final months, Cassini will provide us a definitive measurement of the mass of the rings. This will provide a tight constraint on models of the origins of the rings which in turn will constrain the story of the dynamic history of the system of moons.

The final 'proximal' orbits of Cassini, with the spacecraft threading the gap between the cloudtops and the inner edge of the rings, will provide images with a resolution of 250 m per pixel on the planet, and less than that in the rings. Stellar occultations will probe the atmosphere of Saturn at new latitudes, helping untangle Saturn's weather. In addition to getting the mass of the rings, we'll also measure subtle variations in the gravitational field of the planet, revealing the internal structure of the planet. Each time we have looked more closely we have seen



(A)

(B)

Figure 8.4. This mosaic of Saturn from Cassini was taken from Saturn's shadow (top). The background light from the different images making up the mosaic has not been removed, leading to the pattern of flares in the background. The Sun is blocked by Saturn, and the side of Saturn facing us is illuminated by light reflected onto the atmosphere from the rings themselves. The equator of the planet is completely dark because the rings are so thin that from Saturn's equator they are virtually invisible and reflect no light back to the equator. The north pole is dark because the rings are below the horizon from that vantage point, while the rings themselves obstruct our view of portions of the southern hemisphere. The lower detail shows the Earth, visibly bluish, seen through the gap between the G and E rings. Examined in detail (upper left), the Moon is visible. At left, Enceladus can be seen in the E ring with tendrils of ice crystals spreading out to form the ring. Image Credit: NASA/JPL/SSI.

something new. Cassini's Grand Finale will doubtless continue that trend. On September 15, 2017, on its 293rd orbit of Saturn, Cassini will plunge into Saturn's atmosphere, its large antenna pointed Earthward and transmitting data until friction with the atmosphere causes the spacecraft to turn away from home one last time. Thus will end the data-collection phase of one of the most successful missions of scientific exploration of the cosmos, but the discoveries will continue for years. In our focus and determination to collect the best data and maximize the return from the mission, we have often not had as much time as we need to process, analyze, model and understand the wealth of observations. As we build and fly the next generation of planetary probes, we will continue the journey of discovery at Saturn with the wealth of data from Cassini.

Perhaps the greatest legacy of Cassini–Huygens is the new perspective it provides us on our place in the solar system and the history of our little corner of the Galaxy (figure 8.4).

The Cassini–Huygens mission is a joint venture of seventeen nations, led by NASA and the European Space Agency, and the Italian Space Agency. It is a purely scientific undertaking involving more than 5000 individual scientists and engineers paid for by the people of the nations involved[2]. Its results are freely available to the world and are a testament to human curiosity and what we can accomplish with even modest resources when we work together.

Further reading

The saturn.jpl.nasa.gov website is an excellent portal to images and graphics from the mission, as well as detailed information about the spacecraft and the mission itself.

[2] The US share over the course of the mission was about 30 cents per person per year.