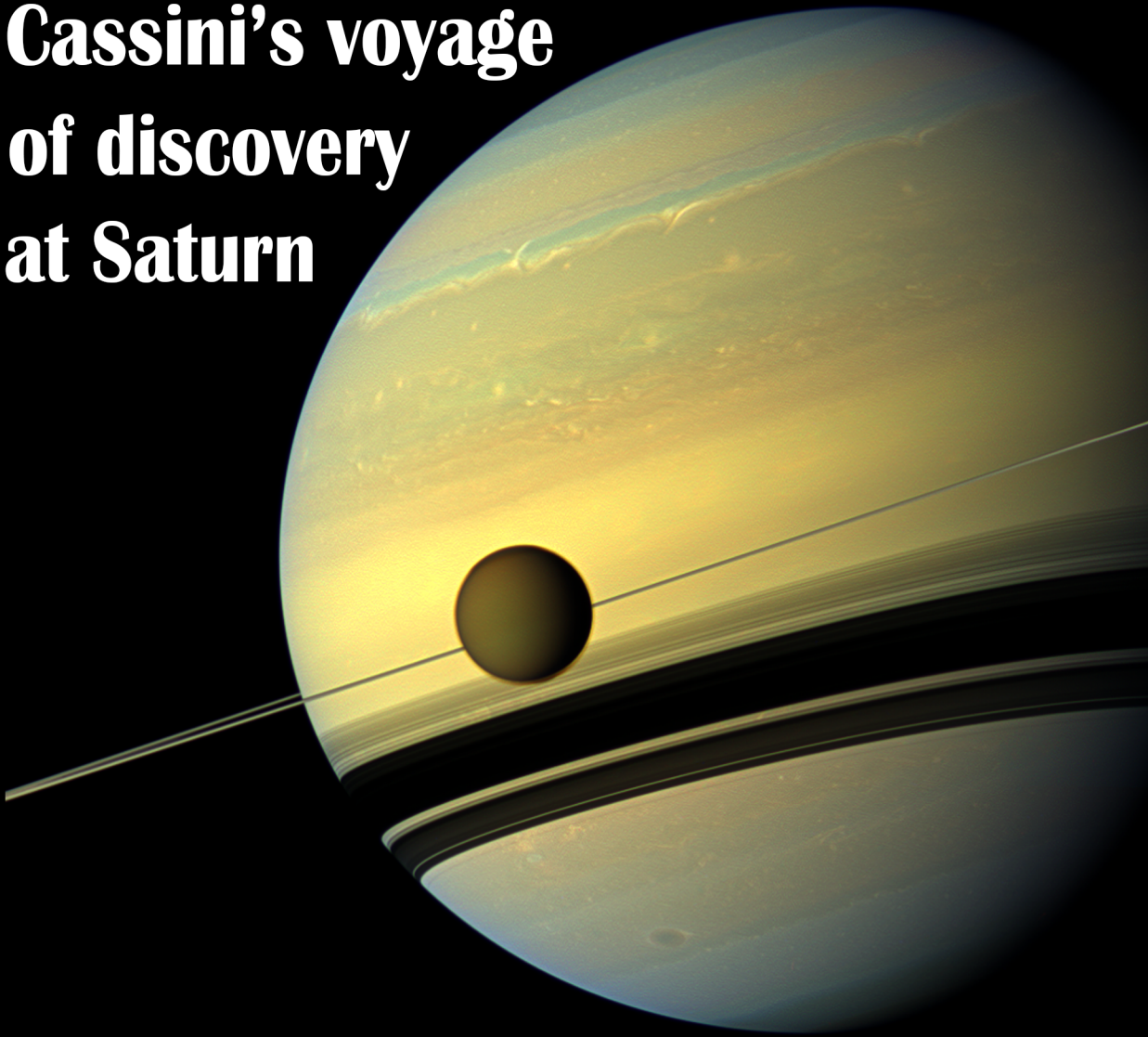


The Ringed Planet

Cassini's voyage
of discovery
at Saturn



Joshua Colwell

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University of Central Florida, USA

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In memory of my father. Always an inspiration.

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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'.

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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



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

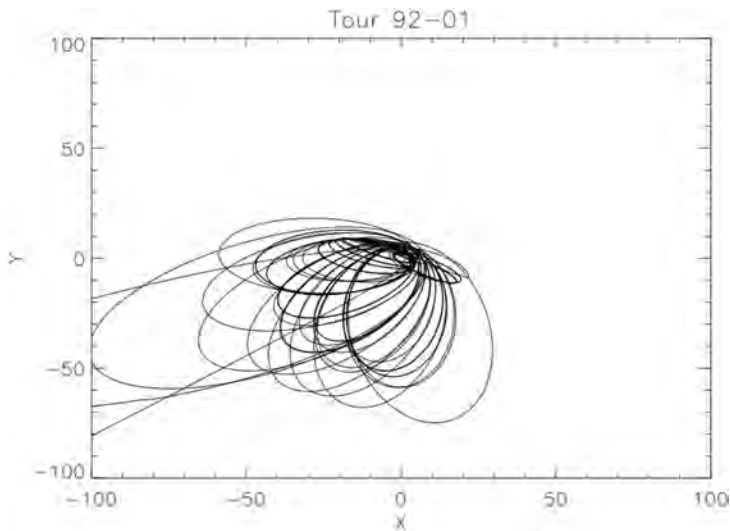


Figure 1.2. The figure shows the path of Cassini in ‘tour’ 92-01 as seen from above Saturn’s north pole. The units on the x - and y -axes are in Saturn radii.

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 Earth¹. 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 Tour². 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 Orbiter³ 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

²The 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'.

³Orbiter 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'.

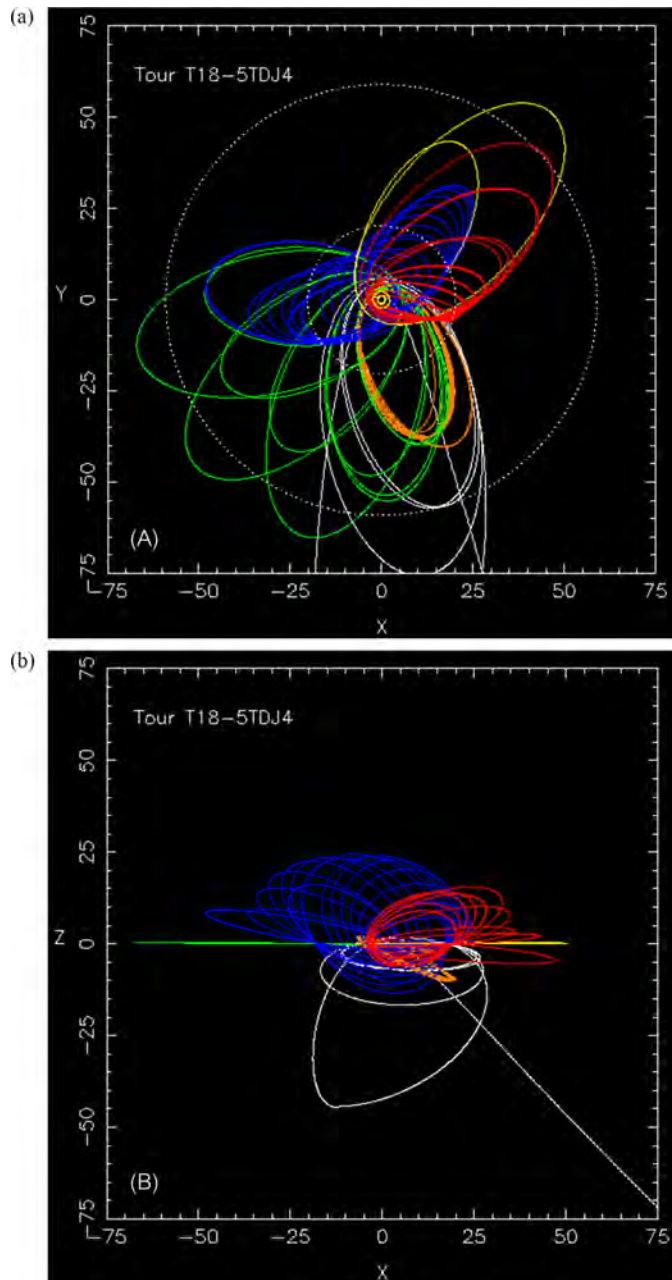


Figure 1.3. (a) The colored lines show the path of Cassini for four years viewed from above Saturn’s north pole in the selected tour T18-5TDJ4. The colors indicate different phases of the mission. The two yellow circles at the center are Saturn and the outer edge of the rings. The white dashed lines 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.

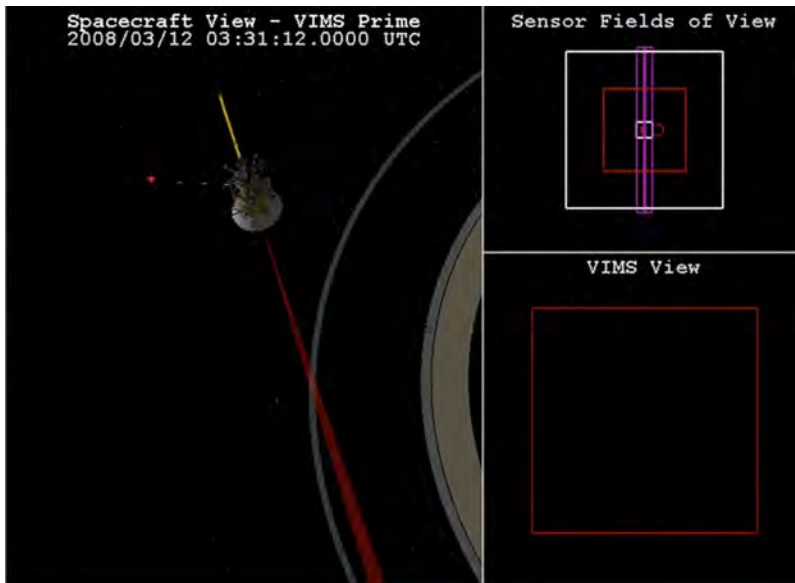


Figure 1.4. Illustration of the observation plan for the flyby of Enceladus on Cassini's 61st orbit of Saturn. The different panels show the maneuvers of Cassini and the views of the different instruments responsible for observations during those times. Movie Credit: NASA/JPL.

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.

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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 portend 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

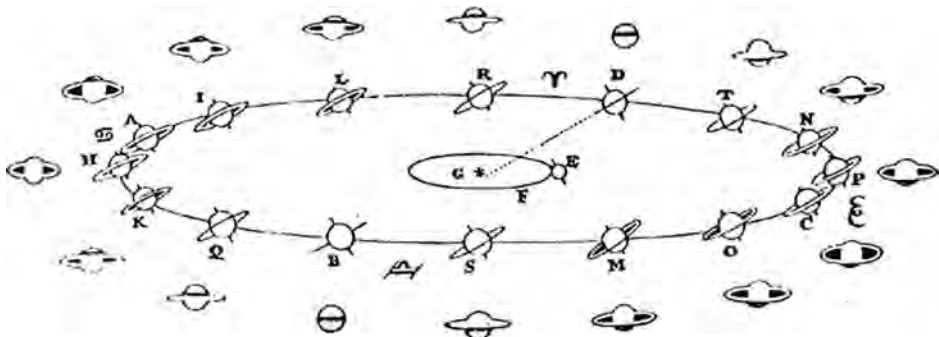


Figure 2.1. Christiaan Huygens' geometric model of Saturn's rings, the first to correctly explain the odd appearance of Saturn through the telescopes of the first half of the 17th century. The Sun is marked by the asterisk at the center, and the orbits of the Earth (E) and Saturn are shown. With Saturn's 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 AU¹. 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.