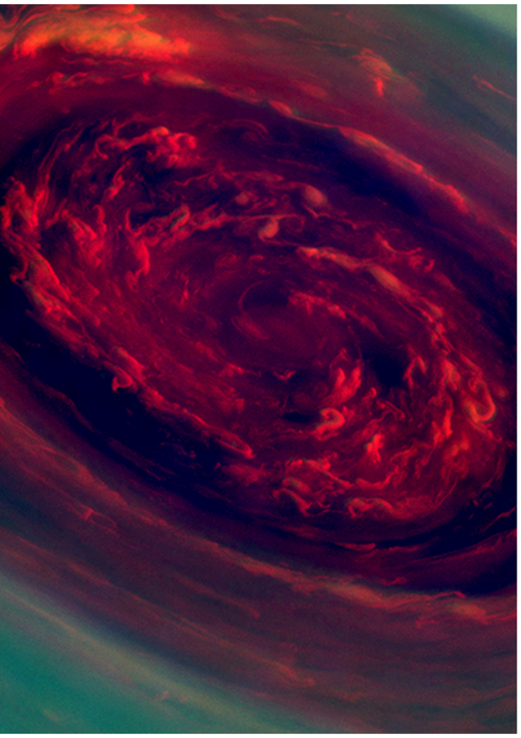

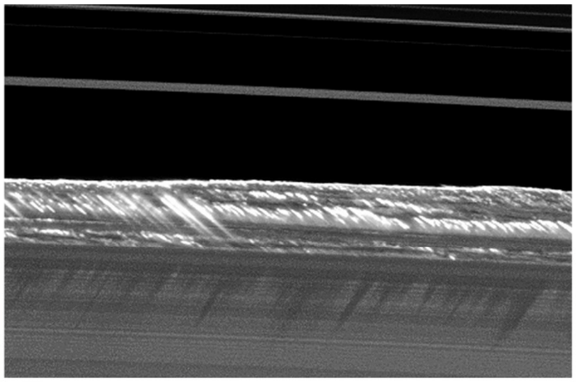

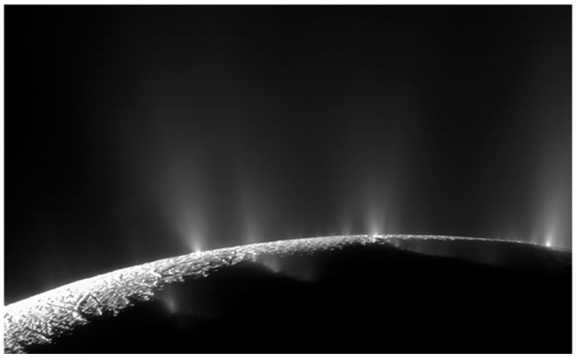

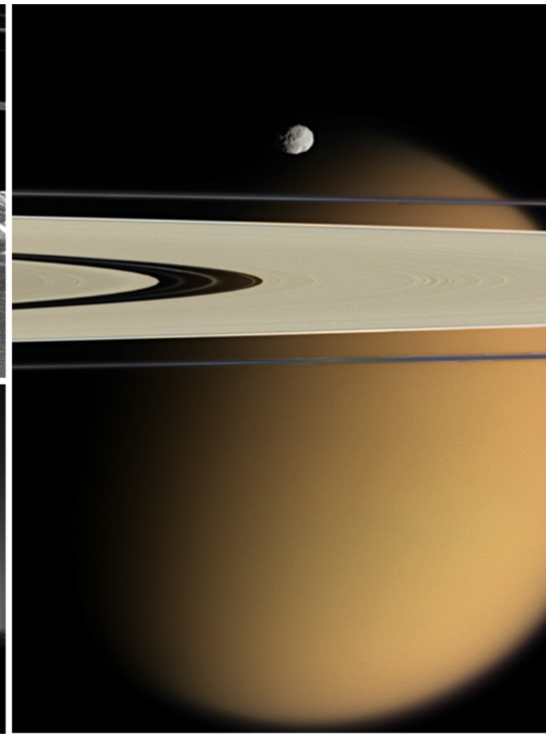

# MISSION SCIENCE HIGHLIGHTS AND SCIENCE OBJECTIVES ASSESSMENT

Cassini-Huygens, humanity's most distant planetary orbiter and probe to date, provided the first in-depth, close up study of Saturn, its magnificent rings and unique moons, including Titan and Enceladus, and its giant magnetosphere. Discoveries from the Cassini-Huygens mission revolutionized our understanding of the Saturn system and fundamentally altered many of our concepts of where life might be found in our solar system and beyond. Cassini-Huygens arrived at Saturn in 2004, dropped the parachuted probe named Huygens to study the atmosphere and surface of Saturn's planet-sized moon Titan, and orbited Saturn for the next 13 years making remarkable discoveries. When it was running low on fuel, the Cassini orbiter was programmed to vaporize in Saturn's atmosphere in 2017 to protect the ocean worlds, Enceladus and Titan, where it discovered potential habitats for life.

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## EXECUTIVE SUMMARY

The primary goal of Cassini-Huygens is to conduct an in-depth exploration of the Saturn system [NASA 1989].

The scientific findings and discoveries of the Cassini-Huygens mission revolutionized our understanding of the Saturn system. This international mission consisted of the Cassini Saturn orbiter and the Huygens Titan probe. With 19 participating countries, the project was an archetype for effective international collaboration.

Overall, the Cassini-Huygens mission was a tremendous success, meeting or exceeding essentially all of its science goals listed in the 1989 Cassini and Huygens Announcements of Opportunity (AOs) and in the Cassini Traceability Matrices first defined in 2007 near the end of the Prime Mission (PM). A complete assessment of these objectives is given in a set of color-coded tables in the Project Science Assessment section.

Due to the very broad scope of the Cassini-Huygens mission, this short overview just scratches the surface of the breadth and depth of Cassini-Huygens' scientific findings. The details of the scientific findings of the mission, including discipline and team science assessments, can be found in the following reports in Section 3. They provide in-depth information on the many investigations that constitute the Cassini-Huygens mission. A concise overview of the scientific findings of Cassini's 13-year mission can be found in Spilker [2019].

A vast amount of unique scientific data was returned over Cassini's 13-year mission and a large volume of that data has yet to be thoroughly analyzed and interpreted. Planetary scientists continue to analyze these data, and will do so for decades to come. All of the Cassini data and supporting information are stored in the Planetary Data System (PDS), available for analysis by future generations of planetary scientists.

The following sections present a brief history of the mission, ties to the previous Decadal Survey, and a short mission overview. The chapter includes the mission science objectives and a project assessment of those objectives, as well as the mission's top science highlights and major open questions. The Cassini-Huygens mission successfully answered a large number of scientific questions and posed many new ones, setting the stage for future missions to Saturn and the outer planets.

### Origin of the Cassini Mission

Three trailblazing spacecraft, Pioneer 11 in 1979, Voyager 1 in 1980, and Voyager 2 in 1981, flew past Saturn and provided short, fleeting glimpses of this unique system, including the giant moon, Titan. Beginning in 2004, NASA's Cassini spacecraft became the first robotic craft to orbit Saturn and perform detailed seasonal and temporal studies. In 2005, the European Space Agency's (ESA) Huygens probe, carried by the Cassini orbiter, was the first human-made object to land on an outer planet moon, Titan.

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The Cassini orbiter was named after the Italian/French astronomer Giovanni Domenico Cassini, who discovered several Saturnian satellites and ring features, including the Cassini division, between 1671–1685. The Titan probe was named after the Dutch astronomer Christiaan Huygens who discovered Titan in 1655.

Cassini-Huygens was an international flagship mission, a cooperative undertaking by NASA, ESA, and the Italian space agency (Agenzia Spaziale Italiana (ASI)). Initial conversations about this mission began not long after the Voyager flybys in the early 1980s. The Voyager instruments were unable to penetrate Titan's thick photochemical haze and many new questions were raised by these flybys. Discussions and planning for a return mission to Saturn, including an in-depth study of the system and a probe into Titan's atmosphere, spanned many years. Some of the discussion that follows can also be found in the Space Science Reviews chapter by Matson et al. [2002].

Formal discussions began in June 1982 when a Joint Working Group was formed by the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Science in the United States. The charter of this Joint Working Group was to study possible modes of cooperation between the United States and Europe in the field of planetary science. Seven years later, after much discussion and many meetings between these international partners, the Cassini and Huygens AOs were released in 1989.

The scientific objectives for the mission and the implementation approach were developed further by the work of the Joint NASA/ESA Assessment Study that was carried out in mid-1984 through 1985, and in 1988. These study groups defined the scientific objectives for the Cassini-Huygens mission and published them in the group's final reports [ESA 1985, 1988]. These objectives then became formally established when they were incorporated into both the NASA and ESA Announcements of Opportunity [ESA 1989; NASA 1989, 1991]. Early summaries of the mission can be found in Lebreton [1991], a book edited by Spilker [1997], and in Matson et al. [2002].

## Instrument Teams and Interdisciplinary Investigations

Prior to issuing the Announcements of Opportunity, NASA, ESA, and ASI carried out informal discussions regarding organization and management of the Cassini-Huygens mission. These agreements were formalized in a Memoranda of Understanding (MOUs) between NASA and ESA, signed in 1990, and between NASA and ASI, signed in 1993. The scientific organization of the mission evolved from these memoranda.

The selections of scientific instruments and facility teams were coordinated between NASA and ESA. Investigations for the Huygens probe were announced by ESA in September 1990, and NASA announced Saturn orbiter selections in November 1990. Both agencies also selected interdisciplinary investigations. The ESA Huygens selection was comprised of six Principal Investigator (PI) instruments and three interdisciplinary science (IDS) investigations. The initial NASA Cassini selection was comprised of seven PI-led instruments, four facility instruments, and seven IDS investigations. Facility instruments were scientific instruments already selected and defined by NASA to be part of the Cassini payload (e.g., the imaging cameras). Scientists proposed to be Team Members (TMs) or Team Leaders (TLs) for these predefined instruments. PI-led instruments included a full instrument proposal, along with a proposed list of Co-Investigators (Co-Is). IDSs proposed scientific investigations relevant to the mission. With the death of NASA-selected IDS James Pollock in 1994, the number of NASA-selected IDS investigations was reduced to six. Absent from the proposed Cassini instruments was one capable of measuring the properties of Titan's upper atmosphere. Such an instrument was regarded as critical to the mission, so in May 1991 NASA issued a second AO, for the Ion and Neutral Mass Spectrometer (INMS) TL and TMs. The results of that selection were announced in February 1992. For facility instruments, NASA selected a TL and TMs, while for PI-led instruments, NASA selected the PI along with his/her proposed team of Co-Is.

Cassini and Huygens accommodated 27 major scientific investigations that were supported by 18 specially designed instruments, 12 on the Cassini orbiter and 6 on the Huygens probe. Lists of the instrument and IDS investigations for Cassini and Huygens can be found in Tables 3-1 and 3-2.

The flight operations of the Cassini mission were carried out at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The data were collected at NASA's Deep Space Network (DSN) stations, with support at times from ESA stations, and sent to the instrument teams. The operations of the Cassini instruments were distributed to their home institutions. Cassini's distributed operations represented a paradigm shift from previous flagship missions, such as Voyager and Galileo, where operations were conducted primarily at JPL. The instrument teams analyzed their respective instrumental data and prepared instrumental operation sequences at their home institution and transmitted them to JPL for uplink. The flight operations of the Huygens probe were carried out from ESA's European Space Operations Center (ESOC) in Darmstadt, Germany, where the Huygens Operations Center (HPOC) was also established.

**Table 3-1. Cassini orbiter investigations. If two scientists are listed, the first individual was the PI or TL at the time of AO selection in 1990. The second name is the individual who was leading the instrument team at the end of the mission, with a transition at some point during the mission.**

| Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
|---|---|---|
| Cassini Plasma Spectrometer (CAPS) | D. Young (PI), Southwest Research Institute<br>J.H. Waite (PI), Southwest Research Institute | In situ study of plasma within and near Saturn's magnetic field |
| Cosmic Dust Analyzer (CDA) | E. Grün (PI), Max Planck Institut für Kernphysik<br>R. Srama (PI), Universität Stuttgart | In situ study of ice and dust grains in the Saturn system |
| Composite Infrared Spectrometer (CIRS) | V. Kunde (PI), NASA Goddard Space Flight Center<br>F.M. Flasar (PI), Goddard Space Flight Center | Temperature and composition of surfaces, atmospheres, and rings within the Saturn system |
| IDS – Magnetosphere and Plasma | M. Blanc (IDS), Research Institute of Astrophysics and Planetology, Toulouse | Interdisciplinary study of plasma circulation and magnetosphere-ionosphere coupling |
| IDS – Rings and Dust | J. Cuzzi (IDS), NASA Ames Research Center | Interdisciplinary study of rings and dust within the Saturn system |
| IDS – Magnetosphere and Plasma | T. Gombosi (IDS), University of Michigan | Interdisciplinary study of the plasma environment in Saturn's magnetosphere |
| IDS – Atmospheres | T. Owen (IDS), University of Hawaii | Interdisciplinary study of the atmospheres of Titan and Saturn |
| IDS – Satellites | L. Soderblom (IDS), U.S. Geological Survey | Interdisciplinary study of the satellites of Saturn |

**Table 3-1. Cassini orbiter investigations. If two scientists are listed, the first individual was the PI or TL at the time of AO selection in 1990. The second name is the individual who was leading the instrument team at the end of the mission, with a transition at some point during the mission.**

| Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
|---|---|---|
| IDS – Aeronomy and Solar Wind Interaction | D. Strobel (IDS), Johns Hopkins University | Interdisciplinary study of aeronomy in the Titan and Saturn atmospheres |
| IDS – Origins | J. Pollock (IDS), NASA Ames Research Center (deceased 1994) | Interdisciplinary study of the origin and evolution of the Saturn system |
| Ion and Neutral Mass Spectrometer (INMS) | J.H. Waite (TL), Southwest Research Institute | In-situ compositions of neutral and charged particles within the Saturn magnetosphere |
| Imaging Science Subsystem (ISS) | C. Porco (TL), Space Science Institute | Multispectral imaging of Saturn, Titan, rings, and the icy satellites to observe their properties |
| Dual Technique Magnetometer (MAG) | D. Southwood (PI), Imperial College<br>M. Dougherty (PI), Imperial College | Study of Saturn's magnetic field and interactions with the solar wind |
| Magnetospheric Imaging Instrument (MIMI) | S. Krimigis (PI), Applied Physics Laboratory<br>D. Mitchell (PI), Applied Physics Laboratory | Global magnetospheric imaging and in-situ measurements of Saturn's magnetosphere and solar wind interactions |
| Titan Radar Mapper (RADAR) | C. Elachi (TL), NASA Jet Propulsion Laboratory | Radar imaging, altimetry, and passive radiometry of Titan's surface |
| Radio and Plasma Wave Science (RPWS) | D. Gurnett (PI), University of Iowa<br>W. Kurth (PI), University of Iowa | Measure the electric and magnetic fields and electron density and temperature in the interplanetary medium and within the Saturn magnetosphere |
| Radio Science Subsystem (RSS) | A. Kliore (TL), NASA Jet Propulsion Laboratory<br>D. French (TL), Wellesley College | Study of atmospheric and ring structure, gravity fields, and gravitational waves |
| Ultraviolet Imaging Spectrograph (UVIS) | L. Esposito (PI), University of Colorado | Spectra and low-resolution imaging of atmospheres and rings for structure, chemistry, and composition |
| Visible and Infrared Mapping Spectrometer (VIMS) | R. Brown (TL), NASA Jet Propulsion Laboratory | Spectral mapping to study composition and structure of surfaces, atmospheres, and rings |

**Table 3-2. Huygens probe investigations. The table below lists the Huygens instrument and IDS investigations as selected in response to the Huygens 1989 AO. (Table after Matson et al. [2002])**

| Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
|---|---|---|
| Aerosol Collector Pyrolyser (ACP) | G. Israel (PI), CNRS, Service d'Aéronomie | In situ study of clouds and aerosols in the Titan atmosphere |
| Descent Imager and Spectral Radiometer (DISR) | M. Tomasko (PI), University of Arizona | Temperatures and images of Titan's atmospheric aerosols and surface |
| Doppler Wind Experiment (DWE) | M. Bird (PI), Universität Bonn | Study of winds from their effect on the *Probe* during the Titan descent |
| Gas Chromatograph and Mass Spectrometer (GCMS) | H. Niemann (PI), NASA Goddard Space Flight Center | In situ measurement of chemical composition of gases and aerosols in Titan's atmosphere |
| Huygens Atmospheric Structure Instrument (HASI) | M. Fulchignoni (PI), Observatoire de Paris-Meudon | In situ study of Titan atmospheric physical and electrical properties |
| IDS – Titan Aeronomy | D. Gautier (IDS), Observatoire de Paris-Meudon | Interdisciplinary study of the aeronomy of Titan's atmosphere |
| IDS – Titan Atmosphere-Surface Interactions | J. Lunine (IDS), Cornell University | Interdisciplinary study of Titan atmosphere-surface interactions |
| IDS – Titan Organic Chemistry | F. Raulin (IDS), Université Paris, Val de Marne | Interdisciplinary study of Titan's chemistry and exobiology |
| Surface Science Package (SSP) | J. Zarnecki (PI), University of Kent | Measurement of the physical properties of Titan's surface |

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## Defining Scientific Objectives

Further development of the AO scientific objectives for Cassini-Huygens was carried out by the Project Science Group (PSG) and the Huygens Science Working Team (HSWT). These groups, chartered by the AOs, were the Program's scientific advisory bodies. Chaired and managed by the Cassini Project Scientist and Huygens Project Scientist, they included interdisciplinary scientists, and participants from all instrument teams. They provided more detail than that specified in the AO requirements, developed Science Traceability Matrices post 2007 for the Equinox and Solstice Missions, and kept the requirements up to date with respect to any new discoveries. In the PSG, this work was done by a set of committees called Discipline Working Groups (DWGs) specializing in each discipline's science requirements and co-chaired by Interdisciplinary Scientists (IDSs) as was envisioned in the AO.

> The Cassini team was an archetype for effective international collaboration, with nineteen participating countries.

The Cassini team of over 350 scientists was organized into five DWGs: Titan, Icy Satellites, Rings, Magnetospheres and Plasma Science (MAPS), and Saturn overseen by the Cassini Project Scientist. These groups were comprised of representatives from the 12 instrument teams and were typically headed by one or more Interdisciplinary Scientists. The Cassini team was an archetype for effective international collaboration, with 19 participating countries. Over the course of the mission, the Cassini family continued to grow by adding a Cassini Participating Scientist Program in addition to the many team associates, postdoctoral fellows, and graduate students. The first class of 12 Participating Scientists was selected in 2011, and included four international scientists. A total of 41 Participating Scientists were selected over five years. A vast amount of unique scientific data was returned over its 13-year mission and a large volume of that data has yet to be thoroughly analyzed and interpreted. Planetary scientists continue to analyze these data, and will do so for decades to come.

The PSG and the HSWT had the responsibility to translate the science requirements into strategies for observing and measuring. The workload was shared by the five DWGs, special working groups such as the Titan Atmospheric Working Group (TAMWG) and Saturn Atmospheric Working Group (SAMWG), and instrument scientific investigation teams under the direction of the PIs and TLs. These strategies were then translated into specific instrumental observations and measurements by the scientists and the engineering and operations staffs of the individual instruments. All of these steps were closely coordinated with the spacecraft operations staffs at JPL and ESOC (for Huygens instruments). Minute-by-minute observation planning was conducted by PSG-sanctioned Operations Science Teams (OSTs; for Titan and Icy Satellite) and project-sanctioned Target Working Teams (TWTs; for Saturn, Rings, and MAPS), which were comprised of instrument team science and engineering representatives along with project-appointed Investigation Scientists (ISs), science planning and spacecraft engineers, and spacecraft operators.

## Cassini Rules of the Road

Before Cassini arrived at Saturn in 2004, the Project Science Group crafted a set of Cassini/Huygens Rules of the Road that were created based on the MAPS Rules of the Road (see Appendix A for more details). The Cassini Rules of the Road offered guidelines for multi-investigation studies using data that were not yet in the PDS. Each Cassini instrument team also crafted its own set of Instrument Rules of the Road to govern their investigations. The Cassini Rules of the Road were the overarching set of Rules of the Road for the mission. The goal of these Rules of the Road was to foster collaboration between the instrument teams.

The Cassini/Huygens Rules of the Road were:

- "Rules of the Road" offers guidelines for multi-investigation studies only and it applies equally and fairly to all Cassini/Huygens teams.
- Cassini/Huygens teams are headed by a PSG member (PI, TL, or IDS). Team members are: TL, official Co-Is, NASA/ESA selected Facility Team Members, and their direct associates. Each associate is "authenticated" by the team lead.
- Each Cassini/Huygens Team has overall responsibility for its investigation, including the initial analysis, interpretation, and publication of their data. Results from single investigations should be published first as much as possible.
- All Cassini/Huygens teams are expected to make available their processed data for Cassini/Huygens team use for multi-investigation studies within a reasonable time (up to 6 months).
- The combined data sets are made available to all interested Cassini/Huygens scientists to identify possible scientifically interesting events.
- The combined data sets may not be published or released without the specific authorization of all contributing Cassini/Huygens teams.
- When data from a Cassini/Huygens team are used in a multi-investigation study:
  - The team lead must be immediately informed of their use.
  - The team must be invited at an early time to participate in the study.
  - The team must be invited to participate in any resulting publication or presentation. First authorship should be fairly divided between the participating teams.
  - Disputes should be resolved at the lowest possible level.
- The Cassini/Huygens science team needs to create a positive atmosphere that strongly discourages misconduct and maximizes science return from the mission.
- It is the responsibility of all Cassini/Huygens teams to make sure that all team members and associates are aware of the Rules of the Road and that they abide by them.

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- These principles were unanimously accepted by the Cassini PSG Executive Session on October 24, 2002.

## Cassini Project Reviews

As the Cassini mission progressed, NASA held a series of reviews during the mission to assess the completed science objectives and to evaluate proposals for extending the mission. In each successive phase of the mission (see Mission Phases section), new science objectives were defined based on Cassini's new findings and discoveries. For example, after the discovery of the Enceladus plume, Enceladus became a science focus for the remainder of the mission, with the addition of 20 more close Enceladus flybys including seven that flew directly through the plume. Other aspects of the mission, such as observing seasonal and temporal changes, were included as well. NASA reviews of Cassini were held in 2007 (proposal for Equinox Mission), 2011 (briefing to Ed Weiler and NASA HQ team), 2012 (Cassini Senior Review 2012), and 2014 (Senior Review 2014), which also included the final year of the mission.

After each review, Cassini received funding to continue its mission. For the 2012 and 2014 Senior Reviews, the Cassini mission proposals were ranked as "Excellent" and at the top of the list of all planetary missions under review.

## System Science

The list of scientific objectives for both the Cassini and Huygens missions was quite extensive. Specific objectives were defined for each type of body in the system—Saturn itself, the rings, Titan, icy satellites, and the magnetosphere. Cassini-Huygens was designed to determine the present state of these bodies, the processes operating on or in them, and the interactions occurring among them. A detailed list of these objectives is given in the Cassini Science Objectives section.

This ability to execute system science was a key aspect of this flagship-class international mission and set this superbly instrumented spacecraft apart. The very complex interactions that occur in systems such as those found at Saturn (e.g., Enceladus jets or Titan's atmosphere and seas) could only be addressed by a diverse, broad array of instruments. The advantage of a flagship-class mission like Cassini-Huygens was its ability to perform an extensive set of exploratory studies, and follow up on those findings. In a number of cases, the Cassini orbiter instruments were used in ways not envisioned when the spacecraft first launched; for instance, flying through Enceladus' plume, and flying through the gap between the innermost ring and the top of Saturn's atmosphere for 22 orbits at the end of the mission.

## Mission Summary

Cassini's 13 years of scientific study spanned almost half a Saturn year, covering late northern winter, spring, and northern summer. The mission ended just a few months after northern summer solstice. Cassini was launched in 1997 and arrived at Saturn in 2004. Cassini's four-year Prime Mission began our exploration of the Saturn system, raising puzzling new questions that were addressed in the extended missions. The two-year Equinox Mission continued observations surrounding the equinox crossing in August 2009 when Saturn's rings were edge-on to the Sun. In 2010, the Cassini Solstice Mission began the final seven years of exploration. It contained equatorial orbits with many targeted icy satellite flybys; inclined orbits with optimal views of Saturn's rings and poles; and finally, highly inclined Ring-Grazing and Grand Finale orbits, diving between the innermost D-ring and upper region of Saturn's atmosphere for the first time by any spacecraft prior to the mission's end on September 15, 2017.

Some of Cassini's most surprising scientific discoveries came from encounters with Saturn's intriguing moons. Enceladus harbors a salty, liquid water ocean beneath its icy crust that is the source for icy jets spewing from its south pole. On giant Titan, methane rain carves river channels and fills lakes and seas with liquid hydrocarbons, mixed with complex prebiotic chemicals that form in its atmosphere and rain to the surface. Titan, too, has an internal liquid water ocean. Cassini's discovery of two ocean worlds at Saturn profoundly changed our ideas of where life might exist in our own solar system and beyond.

Some of Cassini's other amazing findings include a myriad of three-dimensional structures in the dynamic rings driven by interactions with Saturn's moons and interior; a giant Saturn storm that circled the entire planet for most of 2011, while a long-lived hexagonal jet stream discovered by Voyager in 1981 continues to encircle the north polar region. Cassini solved the mystery of Iapetus' dual bright-dark surface, and the true rotation rate of Saturn's interior. The final year of the mission, moving the spacecraft closer to Saturn than ever before, provided an astonishing array of discoveries about the interior of Saturn, its rings, and the gap between the rings and the planet. A summary of some of Cassini's key highlights can be found in the section on Cassini's Top Science Highlights and in Spilker [2019], while more detailed summaries and discussion can be found in the discipline and team reports.

At the conclusion of the Cassini mission, many open questions remained. Some of the top open questions are summarized in the Major Open Questions Resulting from Cassini section. Additional open questions can be found in each discipline and team report. These questions will help guide future missions to Saturn and the outer planets.

## Ties to Planetary Science Decadal Survey Key Questions, Goals, and Objectives

> The Cassini mission enabled significant advances in planetary science and its findings will guide future missions to the outer planets.

Since July 2004, Cassini returned a wealth of data from the Saturn system, yielding amazing discoveries, breathtaking images, expanded awareness of where and how life might exist beyond Earth, and several thousand publications across five interrelated science disciplines: Titan, Icy Satellites, Rings, Magnetosphere and Plasma Science, and Saturn. Over the course of the mission, Cassini implemented Objective 1.5 of the *NASA Strategic Plan 2014*, and addressed the three *Vision and Voyages* (2013–2022 Planetary Science Decadal Survey) cross-cutting themes, including eight of its top ten Priority Questions (Table 3-3). Cassini also tackled all 25 of its Giant Planets and Satellites goals (Table 3-4). The Cassini mission enabled significant advances in planetary science and its findings will guide future missions to the outer planets.

The 13-year Cassini mission at Saturn took full advantage of the spacecraft's diverse set of high-performance instruments to provide unique science throughout the mission. Some of the outstanding opportunities included: 1) observed seasonal processes on Saturn, Titan, icy satellites, the rings, and in the magnetosphere from northern winter to northern summer; 2) studied the time variability of many phenomena, including plume activity on Enceladus and changes in the ring system; 3) made and pursued discoveries in this exceptionally complex and dynamic environment over a variety of inclination and solar illumination angles that are not available from Earth; and 4) determined the gravitational and magnetic fields of Saturn's interior, measured the main-ring mass, and sampled the composition of Saturn's ring particles and upper atmosphere. Cassini was a mission of extraordinary depth and breadth that produced rich data sets.

The Cassini mission provided new data for all 25 objectives listed in the Planetary Science Decadal Survey's Giant Planets and Satellites chapters (Table 3-4). The check marks in Table 3-4 indicate which Decadal Questions were answered by each of the five disciplines. Huygens probe science is included as part of the Titan column.

**Table 3-3. Cassini addressed eight of top ten 2013–2022 Planetary Science Decadal Key Questions.**

| Cross-Cutting Themes | Priority Questions | Addressed by Cassini? |
|---|---|---|
| **Origins** *Building New Worlds* | 1. What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated? | ✓ |
| | 2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions? | ✓ |
| | 3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? | ✓ |
| **Habitability** *Planetary Habitats* | 4. What were the primordial sources of organic matter, and where does organic synthesis continue today? | ✓ |
| | 5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged? | |
| | 6. Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now? | ✓ |
| **Evolution** *Workings of Solar Systems* | 7. How do the giant planets serve as laboratories to understand Earth, the solar system and extrasolar planetary systems? | ✓ |
| | 8. What solar system bodies endanger and what mechanisms shield Earth's biosphere? | |
| | 9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres lead to a better understanding of climate change on Earth? | ✓ |
| | 10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time? | ✓ |

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**Table 3-4. Cassini's Science Objectives thoroughly addressed all 25 of the Planetary Science Decadal Survey Goals and Objectives for Giant Planets and Satellites.**

| *Vision & Voyages* Planetary Science Decadal Survey 2013–022 | | | Cassini Science Disciplines | | | | |
|---|---|---|---|---|---|---|---|
| Chap-ters | Science Goals | Objectives | Titan (includes Huygens) | Icy Satellites | Rings | MAPS | Saturn |
| The Giant Planets: Local Laboratories and Ground Truth for Planets Beyond | Giant planets as ground truth for exoplanets | Understand heat flow and radiation balance in giant planets | | | | | ✓ |
| | | Investigate the chemistry of giant-planet atmospheres | | | | ✓ | ✓ |
| | | Probe interiors of giant planets, including with planetary precession | | | ✓ | ✓ | ✓ |
| | | Explore planetary extrema in the solar system's giant planets | | | ✓ | ✓ | ✓ |
| | | Analyze the properties and processes in planetary magnetospheres | | | | ✓ | ✓ |
| | | Use ring systems as laboratories for planetary formation processes | | | ✓ | ✓ | ✓ |
| | Giant planets' role in promoting a habitable planetary system | Search for chemical evidence of planetary migration | | | | | ✓ |
| | | Explore the giant planets' role in creating our habitable Earth through large impacts | | | | | ✓ |
| | | Determine the role of surface modification through smaller impacts | ✓ | ✓ | ✓ | | ✓ |
| | Giant planets as laboratories for properties and processes on Earth | Investigate atmospheric dynamical processes in the giant-planet laboratory | | | | ✓ | ✓ |
| | | Assess tidal evolution within giant-planet systems | ✓ | ✓ | ✓ | | ✓ |
| | | Elucidate seasonal change on giant planets | | | | ✓ | ✓ |
| | | Evaluate solar wind and magnetic-field interactions with planets | | | | ✓ | ✓ |
| Satellites: Active Worlds and Extreme Environments | How did the satellites of the outer solar system form and evolve? | What were the conditions during satellite formation? | ✓ | ✓ | ✓ | | |
| | | What determines the abundance and composition of satellite volatiles? | ✓ | ✓ | ✓ | | |
| | | How are satellite thermal and orbital evolution and internal structure related? | ✓ | ✓ | ✓ | | |
| | | What is the diversity of geologic activity and how has it changed over time? | ✓ | ✓ | | | |
| | What processes control the present-day behavior of these bodies? | How do active endogenic processes shape the satellites' surfaces and influence their interiors? | ✓ | ✓ | | | |
| | | What processes control the chemistry and dynamics of satellite atmospheres? | ✓ | ✓ | | ✓ | |
| | | How do exogenic processes modify these bodies? | ✓ | ✓ | ✓ | ✓ | |
| | | How do satellites influence their own magnetospheres and those of their parent planets? | ✓ | ✓ | | ✓ | |
| | What are the processes that result in habitable environments? | Where are subsurface bodies of liquid water located, and what are their characteristics and histories? | ✓ | ✓ | | | |
| | | What are the sources, sinks, and evolution of organic material? | ✓ | ✓ | | ✓ | |
| | | What energy sources are available to sustain life? | ✓ | ✓ | | ✓ | |
| | | Is there evidence for life on the satellites? | ✓ | ✓ | | | |

Cassini also responded to 41 of 75 of the Giant Planets and Satellites chapters “Important Questions for the next decade,” and also inspired 29 of them. Some of the Cassini-inspired questions, many of which Cassini answered over the course of the mission, included:

- Does Titan have an internal liquid water ocean?
- Is there active cryovolcanism on Titan?
- How do Titan’s clouds originate and evolve?
- What is the spatial distribution of Enceladus’ heat output, and how has it varied with time?
- Does Enceladus have an internal ocean or some other means of providing large tidal dissipation?
- What mechanisms drive and sustain Enceladus’ plumes and tiger stripe tectonics?
- What is the source of the organic material in the plume of Enceladus?
- Do other Saturnian icy satellites such as Dione and Rhea contribute measurable amounts of neutrals or plasma to Saturn’s magnetosphere?

Other Planetary Science Decadal Important Questions included:

- What mechanism has prolonged Saturn’s thermal evolution?
- How is energy dissipated within giant planets?
- Does helium rain play a role in reducing the He/H in Saturn’s molecular envelope?
- What are the natures of periodic outbursts such as the global upheavals on Jupiter and the infrequent great white spots on Saturn?
- How and why does the atmospheric temperature and cloud composition vary with depth and location on the planet?
- What is the source of energy for the hot coronas/upper atmospheres of all four giant planets?
- What processes control Titan’s weather?
- What can our understanding of the giant planet magnetospheres tell us about the conditions to be expected at extra-solar giant planets?
- How do magnetospheres interact with the solar wind?
- What can the significant differences among ring systems teach us about the differing origins, histories, or current states of these giant planet systems?
- What drives orbital evolution of embedded moonlets; how do they interact with their disks?
- What drives mass accretion in a ring system?

Overall, the Cassini mission was a tremendous success. It addressed objectives across a broad array of scientific disciplines, and followed up on many unexpected discoveries. Cassini's many findings and discoveries will provide a pathfinder for outer planet science in the next Planetary Science Decadal Survey.

# Mission Overview

## Mission Phases

Cassini was designed to address a broad array of objectives across five science disciplines: Titan, Icy Satellites, Rings, Magnetospheres and Plasma Science, and Saturn.

The spacecraft flew with 12 science instruments (Table 3-5): four optical remote sensing (ORS) instruments, two microwave remote sensing instruments, and six MAPS instruments. The Class-A spacecraft subsystems launched with full redundancy, and retain full functionality.

**Table 3-5. Three suites of instruments enable interdisciplinary science investigations.**

| Optical Remote-Sensing Instruments (ORS) | |
|---|---|
| CIRS | Composite Infrared Spectrometer |
| ISS | Imaging Science Subsystem |
| UVIS | Ultraviolet Imaging Spectrograph |
| VIMS | Visible and Infrared Mapping Spectrometer |
| **Microwave Remote-Sensing Instruments** | |
| RADAR | Titan Radar Mapper |
| RSS | Radio Science Subsystem |
| **Magnetosphere and Plasma Science Instruments (MAPS)** | |
| CAPS | Cassini Plasma Spectrometer |
| CDA | Cosmic Dust Analyzer |
| INMS | Ion and Neutral Mass Spectrometer |
| MAG | Dual Technique Magnetometer |
| MIMI | Magnetospheric Imaging Instrument |
| RPWS | Radio and Plasma Wave Science |

Cassini-Huygens left the Earth on October 17, 1997, using a Titan IV/Centaur launch vehicle with Solid Rocket Motor Upgrade (SRMU) strap-ons and a Centaur upper stage. During the 6.7-year journey to Saturn, the spacecraft had gravity assistance from Venus on April 26, 1998, and June 24, 1999, from Earth on August 18, 1999, and from Jupiter on December 30, 2000. Cruise activities were planned to checkout, calibrate, and maintain the instruments as well as characterize the instruments and perform limited science observations (limited by flight software available on the spacecraft as well as cost, scheduling, and workforce constraints).

The Venus-1 flyby occurred on April 26, 1998, just six months after launch. The spacecraft approached Venus from a sunward direction and closest approach occurred just after entering the Sun's shadow for a period of about 15 minutes. At closest approach, the altitude was 284 km, with a velocity relative to Venus of 11.8 km/s.

A repetition of the ATLO "Quiet Test" was conducted to allow instruments to monitor other instruments as they turned on and off, thus providing valuable insight into how to integrate science observations during the Saturn tour.

The Instrument Checkout (ICO-1) sub-phase was September 14, 1998, through March 14, 1999. This sub-phase was characterized by the opposition that occurred on January 9, 1999, and which allowed use of the high-gain antenna (HGA) for downlink since the Earth and Sun were nearly aligned as seen from Cassini. All instruments scheduled checkout activities within a 25-day period centered on opposition. This was the first opportunity since launch to exercise most of the instruments and check status other than routine instrument maintenance. A repetition of the ATLO "Quiet Test" was conducted to allow instruments to monitor other instruments as they turned on and off, thus providing valuable insight into how to integrate science observations during the Saturn tour.

The second Venus (Venus-2) flyby occurred on June 24, 1999. Closest approach occurred at 2030 Universal Time (UT) at an altitude of 603 km with a Venus-relative velocity of 13.6 km/s. Approach to Venus was from the dusk side of the planet. Between Venus-2 and the upcoming Earth flyby, about two dozen activities involving maintenance, calibration, checkout, and science observations were carried out, using all of the Cassini instruments except INMS and CIRS, which were subject to thermal constraints.

The Earth flyby occurred 55 days after the Venus 2 flyby on August, 18, 1999. The spacecraft approached the Earth approximately from the direction of the Sun. Closest approach occurred right after the spacecraft entered the Sun occultation zone. The occultation lasted approximately 30 minutes. The altitude at closest approach was 1175 km, with an Earth-relative velocity of 19.0 km/s.

The MAG boom deployment executed 44 hours prior to Earth closest approach. Within the 24-hour period surrounding Earth flyby, the spacecraft passed in and out of the Earth's magnetosphere. Observations during this time were crucial for magnetometer alignment calibration to ensure that measurements at Saturn would be accurate to meet the major science goal of measuring Saturn's magnetic field orientation to an accuracy of 0.1°.

In addition, activities for CAPS, CDA, MIMI, RPWS, RSS, and VIMS were allowed during the approach to Earth, as well as observations of the Earth's moon for ISS, UVIS, and VIMS. After Earth closest approach, RADAR observations were performed as an end-to-end test of the RADAR system using Earth as a target. A few months later, on January 23, 2000, observations by ISS, VIMS, and UVIS of the distant (1,634,000 km) asteroid 2685 Masursky were conducted. No papers or abstracts were written on this observation.

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A second Instrument Checkout (ICO-2) was conducted during July and August 2000 when the high-gain antenna was routinely in use and in preparation for the upcoming Jupiter flyby. The Jupiter flyby occurred on December 30, 2000, at a distance of 9.7 million km. On October 1, 2000, Jupiter approach science began using a repeating 5-day template. Science conducted by all instruments at Jupiter provided an opportunity to test Saturn observation techniques, ground and flight software, and building and execution of sequences.

After Jupiter, a Gravitational Wave Experiment (GWE) was executed December 2001 and a Conjunction Experiment in June 2002. The GWE preparation included two 1-week test periods starting in early May 2001 and August 2001. Additional GWEs were performed in December 2002 and October 2003.

Limited calibration and science data collection occurred during the Venus and Earth flybys. The scientific results of this mission phase are described in a collection of 11 scientific articles that appeared together in a special issue, “First Results from Cassini: Venus and Earth Swing-Bys” in the *Journal of Geophysical Research: Space Physics* in December 2001. As the spacecraft approached Jupiter, the number of science activities increased. Jupiter observations served as preparation for the four-year tour of the Saturnian system. Many of the science results are summarized in the Discipline and Instrument Reports that follow in this volume (see Volume 1 Sections 3.1 and 3.2).

Orbit insertion at Saturn occurred on July 1, 2004, thus starting 13 years of Cassini observations. The Saturn year is almost 30 Earth-years long and Saturn has an obliquity of almost 27°. Cassini arrived after the start of northern winter for its Prime Mission (Table 3-6 and Figure 3-1). The Prime Mission, completed in mid-2008, had only begun the exploration of the Saturn system, raising puzzling new questions that focused the science objectives of the upcoming extended missions.

**Table 3-6. Summary of Cassini mission phases in the Saturn system.**

| | Mission Phase | Acronym | Dates (Seasons) |
|---|---|---|---|
| | Prime Mission | PM | July 2004—July 2008 |
| Extended Missions | Cassini Equinox Mission | CEM | July 2008—Oct 2010 (equinox) |
| | Cassini Solstice Mission | CSM | Oct 2010—Nov 2016 (early northern spring) |
| | Ring Grazing (F-ring orbits)<br>*Grand Finale (proximal orbits)* | RG<br>*GF* | Nov 2016—April 2017 (late northern spring)<br>April 2017—Sept 2017 (northern summer) |

The fully-funded Cassini Equinox Mission (CEM) continued observations throughout a two-year period surrounding the equinox crossing in August 2009. In 2010, the streamlined (reduced budget) Cassini Solstice Mission (CSM) began seven years of exploration in three phases: CSM-1 was characterized by equatorial orbits including many icy-satellite targeted flybys; CSM-2 was characterized by inclined orbits that gave us optimal views of the rings and poles of Saturn; and the Northern Summer Mission (NSM) designed to witnesses the arrival of northern summer continuing the seasonal study of the Saturn system.

The last nine months of the mission was designed to put Cassini onto a collision course with Saturn. For the first five months, the trajectory included a series of 20 inclined orbits with periapses near the unusually dynamic F-ring and apoapses near Titan's orbit. The last close flyby of Titan put Cassini into orbits with periapse between the innermost D-ring and the upper portions of Saturn's atmosphere for Cassini's last four months. A "goodbye kiss" from Titan, placed Cassini onto its last half orbit and brought the mission to an end collecting data on Saturn's upper atmosphere for as long as the spacecraft could hold steady.

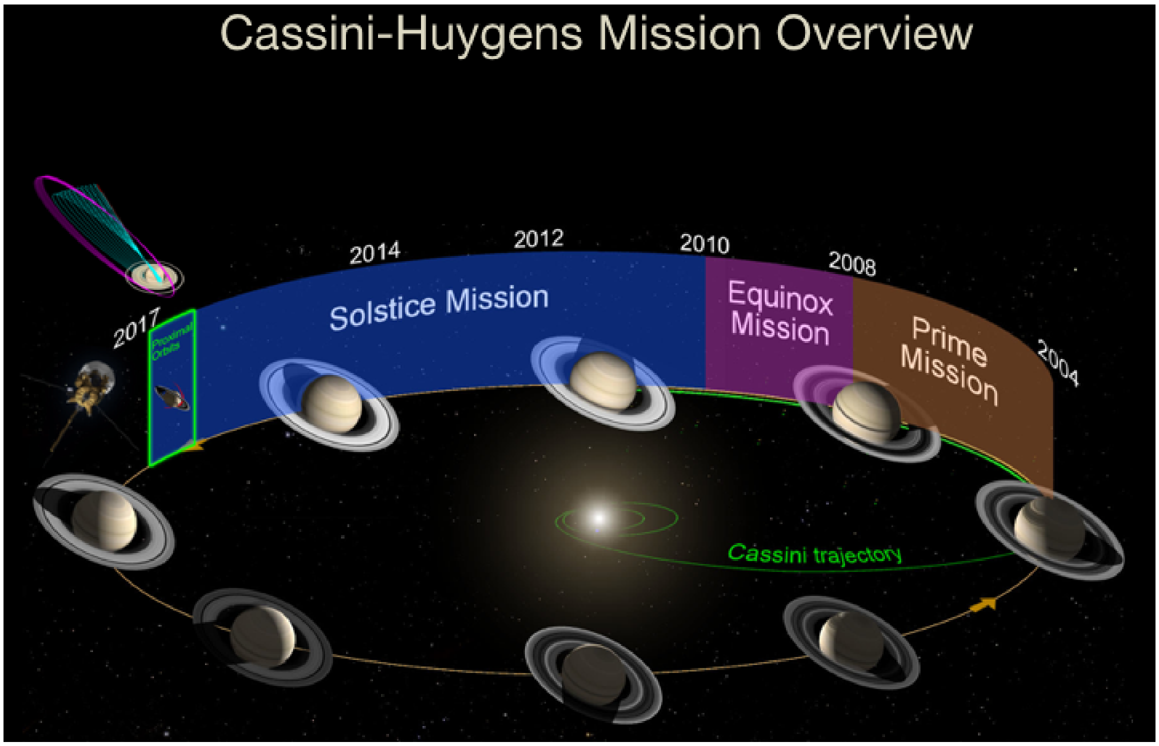


**Figure 3-1. Seasonal coverage and associated phases of the Cassini-Huygens mission to Saturn. The Ring Grazing and Grand Finale phases of the mission are shown in the green box.**

## A Scientifically-Rich Mission

On the surface, Cassini's complete set of orbits, or tour, might look like a giant ball of yarn. When examined more closely, these orbits allowed Cassini to visit multiple targets at key times during the course of half a Saturn year. Multiple flybys of Titan provided gravity assists that shaped the size and orientation of each orbit in Cassini's orbital tour. This unique combination of orbital geometry allowed Cassini to study the complex seasonal changes that occurred throughout the Saturn system as the Sun set in the south and rose to more northerly latitudes in the Saturnian sky. Figure 3-2 illustrates the richness of this tour flown by the spacecraft.

The Prime Mission started roughly two years after northern winter began. It was comprised of 75 orbits, 45 Titan flybys, four (4) Enceladus flyby, and six (6) icy satellite flybys, including Phoebe. Just one year into the exploration, Cassini and Huygens discovered that Titan was an Earth-like world with lakes and rivers and active weather. Cassini also discovered that Enceladus was a satellite with active plumes for the spacecraft to sample. Already, it was clear that scientists wanted to further study both worlds.

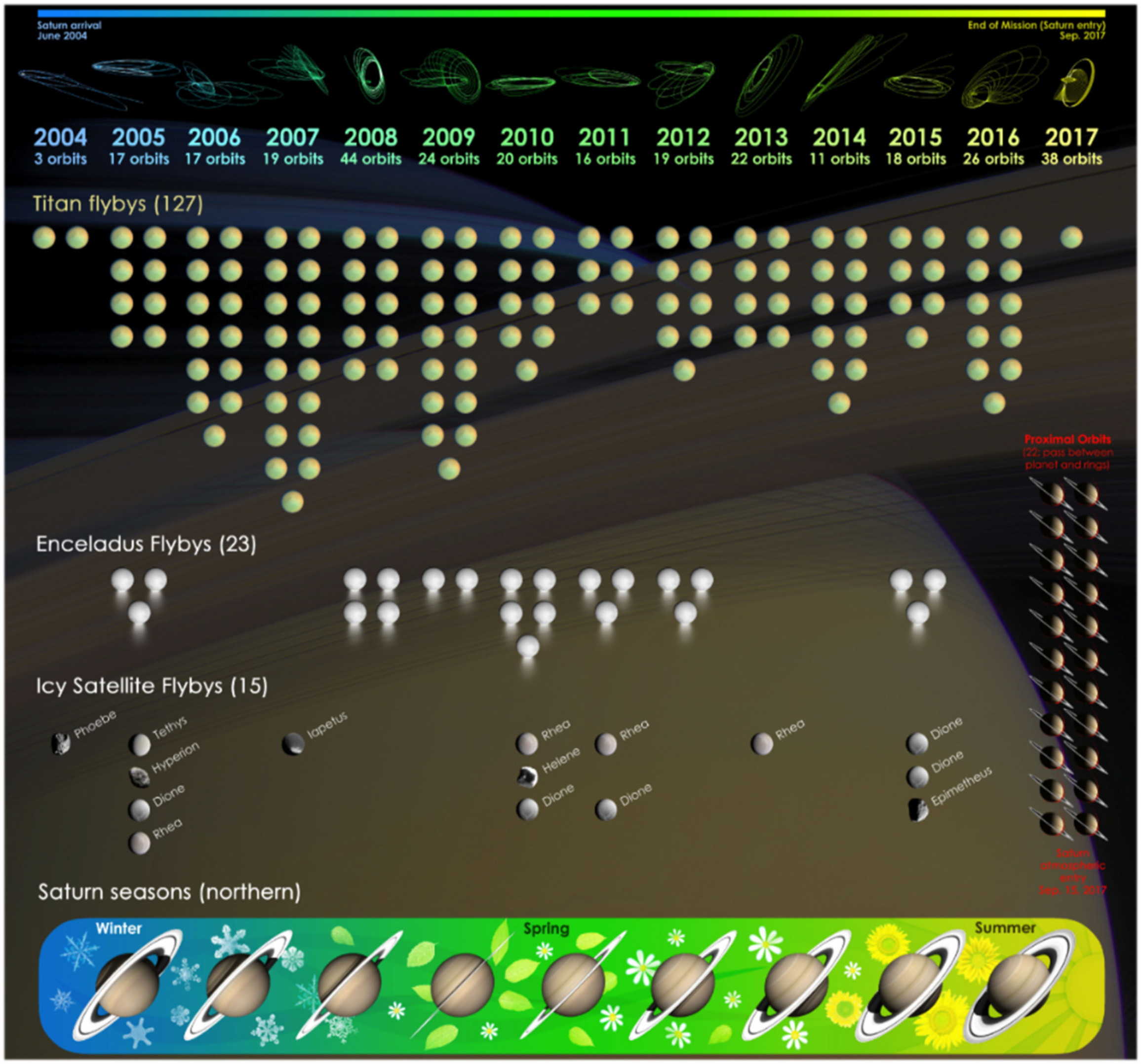


**Figure 3-2. A scientifically-rich mission. From top to bottom: year and orbit, number of Titan flybys, number of Enceladus flybys, number of icy satellite flybys, and Saturn seasons. Cassini's 22 Grand Finale orbits are shown at the far right.**

Cassini's mission was extended by another two years to encompass the years surrounding Saturn's equinox in August 2009 marking the transition from northern winter to northern spring. Orbits were designed to take advantage of the unique viewing of the rings at the time of equinox and to explore the magnetotail. These 60 orbits contained seven (7) additional Enceladus flybys, 26 Titan flybys, and four (4) icy satellite flybys.

With the knowledge and efficiencies gained from six years of flying a healthy spacecraft, mission designers proposed a plan to effectively make use of the remaining fuel onboard to observe the

Saturn system for the entire spring and into solstice (May 2017). Open scientific questions certainly argued for it and paved the way for profound discoveries to be made and provided the opportunity to observe unexpected events (e.g., Saturn's 2010–2011 Great Storm). A total of 160 orbits were executed containing twelve (12) Enceladus, 56 Titan, and twelve (12) icy satellite flybys. The last nine months, the 42 Ring Grazing and Grand Finale orbits, would be the capstone of a remarkable mission.

## Cassini's Last Phase: Capstone of a Remarkable Mission

**Ring Grazing Orbits:** In late 2016, Cassini's trajectory transitioned to a series of 20 Ring Grazing orbits with periapses located within 10,000 km of Saturn's F-ring (Figure 3-3). These orbits provided the high-resolution views of Saturn's F-ring and outer A-ring, in addition to prime viewing conditions for fine-scale ring structures such as propellers (Figure 3-4). They also included the closest flybys of tiny ring moons, including Pan, Daphnis, and Atlas (Figure 3-4). Plasma and dust composition measurements were also conducted in this region.

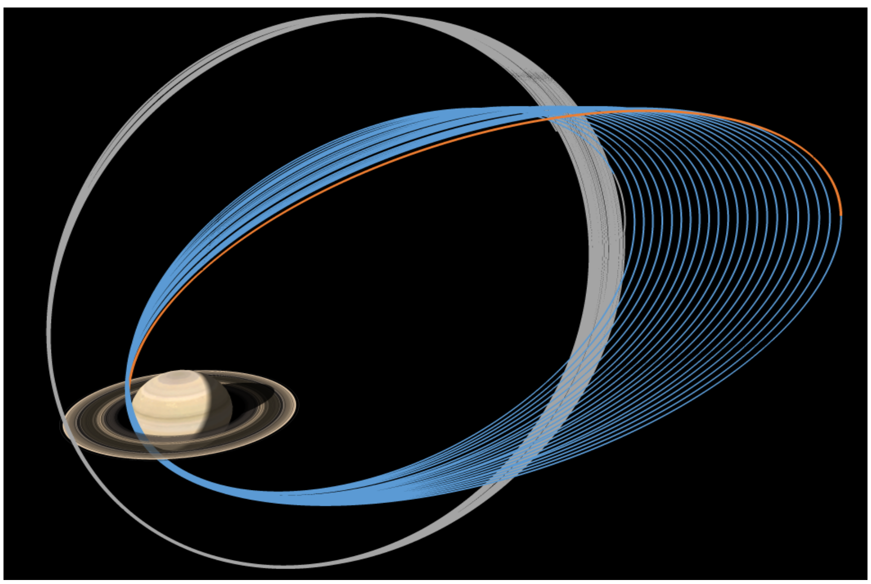

**Figure 3-3. Cassini's 20 Ring Grazing (gray) and Grand Finale (blue) orbits. The last half-orbit (orange) took Cassini into Saturn's atmosphere for vaporization.**

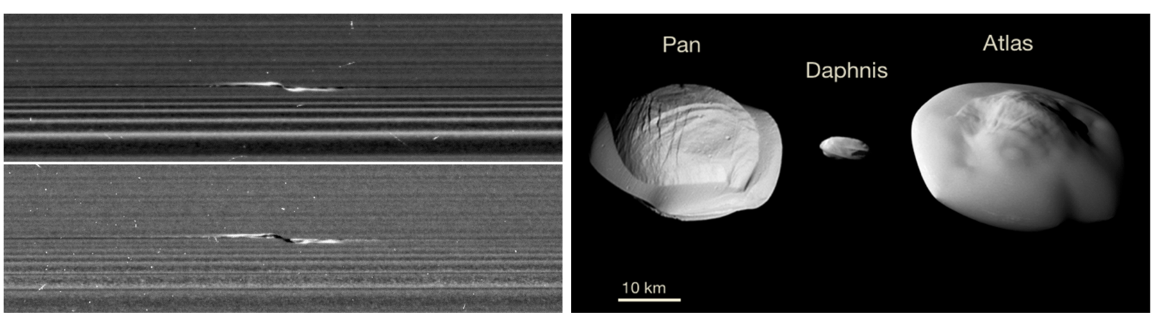


**Figure 3-4. Left: Ring propeller Santos-Dumont on lit and unlit sides of the rings. Right: Comparison of highest resolution images of the ring moons, Pan, Daphnis, and Atlas.**

**Grand Finale Orbits:** A final close flyby of Titan in late April 2017 propelled Cassini across Saturn's main rings and into its Grand Finale orbits. Comprised of 22 orbits, the spacecraft repeatedly dove between Saturn's innermost rings and upper atmosphere (Figure 3-4, blue orbits) attempting to answer fundamental questions unattainable earlier in the mission. The Grand Finale was like a brand-new mission, exploring a region of the Saturn system that was unexplored by Cassini and any previous outer planet spacecraft.

Saturn's gravitational field was measured to unprecedented accuracy, providing information from which constraints on the interior structure of the planet, winds in the deep atmosphere, and mass distribution in the rings could be derived (Figure 3-5). Probing the magnetic field provided data for insight into the physics of the magnetic dynamo, on the structure of the internal magnetic field, and on the location of the metallic hydrogen transition region.

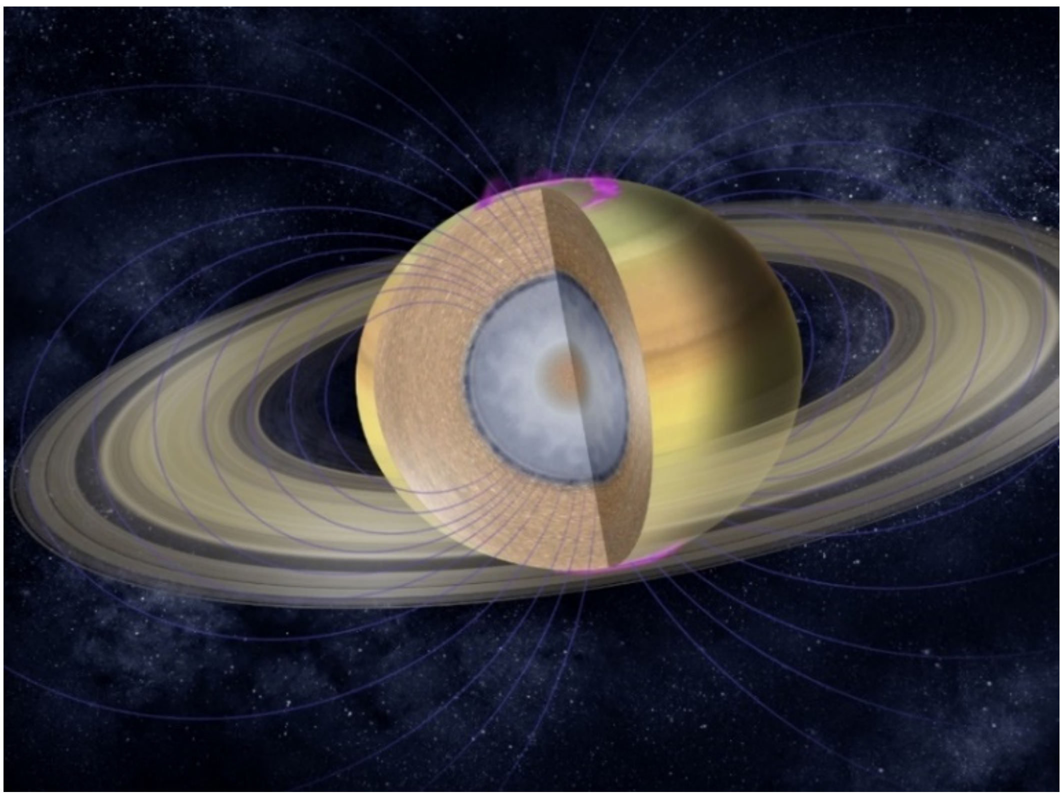

**Figure 3-5. Grand Finale science goals focused on studying ring mass and composition, interior structure, magnetic dynamo, aurora, and atmospheric composition.**

The Grand Finale orbits provided the highest resolution observations ever of both Saturn's C- and D-rings and Saturn's atmospheric weather layer (Figure 3-6). Direct in situ sampling of the ring particle composition and the innermost radiation belts was also achieved. The INMS sampled the exosphere and upper atmosphere for molecules entering and escaping from the atmosphere and water-based molecules originating from the rings. The CDA directly sampled the composition of ring particles from different regions of the main rings for the first time.

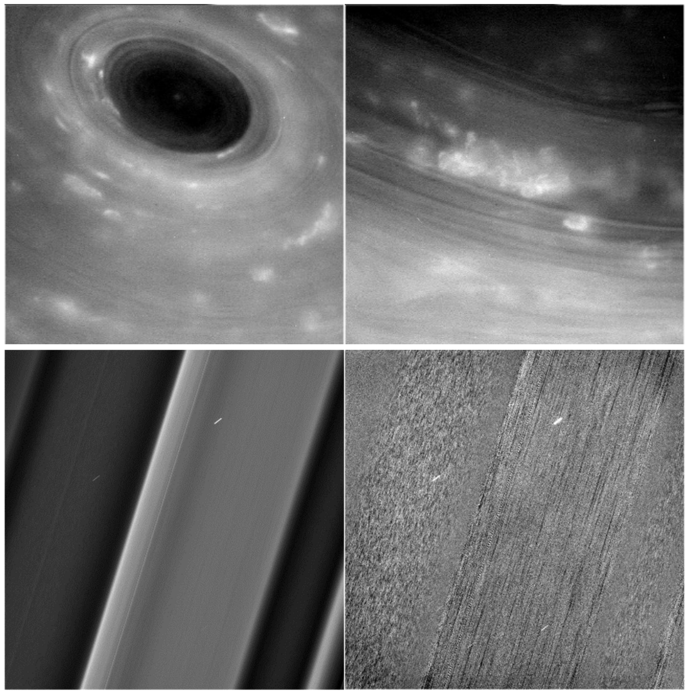

**Figure 3-6. Saturn's north polar vortex (upper left) and convective clouds over the hexagon jet stream (upper right). Image of C-ring "Plateau" features (lower left) and same image after processing (lower right) to reveal differing ring particle "textures" in neighboring regions.**

**Cassini's Final Half-orbit:** The last half-orbit turned the spacecraft into the first Saturn atmosphere probe with all of fields and particle instruments gathering data as long as the spacecraft remained stable. Approximately one additional scale height of atmosphere was probed prior to loss of the radio signal from the spacecraft.

The Cassini mission was a remarkable endeavor, revealing the Saturn system in unprecedented detail. Numerous Cassini discoveries reshaped our thinking about this astoundingly complex system.

## Cassini-Huygens Science Objectives

The Cassini-Huygens science objectives were first defined in the NASA and ESA AOs [ESA 1989; NASA 1989, 1991]. An expanded set of science objectives were later defined in a set of Traceability Matrices that were developed in 2007 as a part of Cassini's first mission extension. As the mission progressed, the Traceability Matrices were updated and refined through three mission extensions, including Senior Reviews in 2012 and 2014 [JPL 2012, 2014], based on Cassini's latest findings. Science objectives from both the AO and Traceability Matrices are briefly listed in the next section, and are explored in more detail in the discipline and instrument team reports in Section 3.2. The Traceability Matrix objectives listed in the following section are those defined for the Cassini Solstice Mission (CSM), and in Cassini's 2014 Senior Review. For the Traceability Matrix objectives, the second letter is either a "C" for seasonal or temporal "Change," or an "N" for "New" science.

## Cassini-Huygens Announcements of Opportunity and Traceability Matrices Science Objectives

### *Huygens Probe AO objectives (see Huygens Discipline Report)*

- Titan Atmospheric Formation and Evolution (H_AO1) – Determine abundances of atmospheric constituents (including any noble gases); establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere.
- Titan Atmospheric Composition and Distribution (H_AO2) – Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photochemistry of the stratosphere; study formation and composition of aerosols.
- Titan Meteorology (H_AO3) – Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges.
- Titan Surface Characteristics and Internal Structure (H_AO4) – Determine the physical state, topography, and the composition of the surface; infer the internal structure of the satellite.
- Titan Upper Atmosphere (H_AO5) – Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

### *Icy Satellites AO objectives (see Icy Satellites Discipline Report)*

- Icy Satellite Geology and History (I_AO1) – Determine the general characteristics and geological histories of the satellites.
- Icy Satellite Surface and Crustal Modifications (I_AO2) – Define the mechanisms of crustal and surface modifications, both external and internal.
- Icy Satellite Surface Composition (I_AO3) – Investigate the compositions and distributions of surface materials, particularly dark, organic rich materials and low melting point condensed volatiles.
- Icy Satellite Interior Properties (I_AO4) – Constrain models of the satellites' bulk compositions and internal structures.
- Icy Satellite Magnetosphere and Ring Interactions (I_AO5) – Investigate interactions with the magnetosphere and ring systems and possible gas injections into the magnetosphere.

## *Icy Satellites CSM Traceability Matrix objectives (see Icy Satellites Discipline Report)*

- Enceladus Seasonal Changes (IC1a) – Identify long-term secular and seasonal changes at Enceladus, through observations of the south polar region, jets, and plumes.
- Enceladus Ocean (IN1a) – Determine the presence of an ocean at Enceladus as inferred from induced magnetic field and plume composition, search for possible anomalies in the internal structure of Enceladus as associated with plume sources, and constrain the mechanisms driving the endogenic activity by in situ observations and remote sensing.
- Mid-sized Satellites (IN1b) – Complete the comparative study of Saturn's mid-sized satellites, their geological and cratering histories, and interactions with the Saturn system, with remote sensing of Mimas at the highest resolution possible in order to understand the mechanisms behind its unique thermal properties discovered by Cassini.
- Dione (IN1c) – Determine whether Dione exhibits evidence for low-level activity, now or in recent geological time.
- Rhea (IN2a) – Determine whether there is ring material orbiting Rhea, and if so, what its spatial and particle size distribution is.
- Tethys (IN2b) – Determine whether Tethys contributes to the E-ring and the magnetospheric ion and neutral population.
- Satellite Interiors (IN2c) – Determine the extent of differentiation and internal inhomogeneity within the icy satellites, especially Rhea and Dione.
- Small Moons (IN2d) – Observe selected small satellites to quantify the movement of Enceladus material through the system, the history of satellite collisions/breakup, interaction with ring material as indicated by surface properties/composition, and cratering rates deep in the Saturnian system.
- Hyperion (IN2e) – Understand the unusual appearance of Hyperion with remote sensing observations of the highest resolution possible.
- Iapetus (IN2f) – Use remote sensing of Iapetus to test models for the albedo heterogeneity of the satellite. Quantify the effect of the newly-discovered Phoebe ring on the properties of Iapetus' surface.

## *Titan AO objectives (see Titan Discipline Report)*

- Titan Atmospheric Formation and Evolution (T_AO1) – Determine abundances of atmospheric constituents (including any noble gases), establish isotope ratios for abundant elements, constrain scenarios of formation and evolution of Titan and its atmosphere.

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- Titan Atmospheric Composition and Distribution (T_AO2) – Observe vertical and horizontal distributions of trace gases, search for more complex organic molecules, investigate energy sources for atmospheric chemistry, model the photochemistry of the stratosphere, study formation and composition of aerosols.
- Titan Meteorology (T_AO3) – Measure winds and global temperatures; investigate cloud physics, general circulation, and seasonal effects in Titan's atmosphere; search for lightning discharges.
- Titan Surface Characteristics and Internal Structure (T_AO4) – Determine the physical state, topography, and composition of the surface; infer the internal structure of the satellite.
- Titan Upper Atmosphere (T_AO5) – Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

### *Titan CSM Traceability Matrix objectives (see Titan Discipline Report)*

- Titan's Great Seas (TC1a) – Determine seasonal changes in the methane-hydrocarbon hydrological cycle: of lakes, clouds, aerosols, and their seasonal transport.
- Titan's Global Seasons (TC1b) – Determine seasonal changes in the high-latitude atmosphere, specifically the temperature structure and formation and breakup of the winter polar vortex.
- Titan-Magnetosphere Interaction (TC2a) – Observe Titan's plasma interaction as it goes from south to north of Saturn's solar-wind-warped magnetodisk from one solstice to the next.
- Titan's Surface (TN1a) – Determine the types, composition, distribution, and ages, of surface units and materials, most notably lakes (i.e., filled vs. dry and depth; liquid vs. solid and composition; polar vs. other latitudes and lake basin origin).
- Titan's Interior Ocean (TN1b) – Determine internal and crustal structure: Liquid mantle, crustal mass distribution, rotational state of the surface with time, intrinsic and/or internal induced magnetic field.
- Titan Atmospheric Composition (TN1c) – Measure aerosol and heavy molecule layers and properties.
- Titan Atmospheric Structure (TN2a) – Resolve current inconsistencies in atmospheric density measurements (critical to a future Flagship mission).
- Titan's Icy Shell (TN2b) – Determine icy shell topography and viscosity.
- Titan Meteorology (TN2c) – Determine the surface temperature distribution, cloud distribution, and tropospheric winds.

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### *Saturn AO objectives (see Saturn Discipline Report)*

- Saturn Temperature, Clouds, Composition (S_AO1) – Determine temperature field, cloud properties, and composition of the atmosphere of Saturn.
- Saturn Winds and Weather (S_AO2) – Measure the global wind field, including wave and eddy components; observe synoptic cloud features and processes.
- Saturn Interior Structure and Rotation (S_AO3) – Infer the internal structure and rotation of the deep atmosphere.
- Saturn Ionosphere-Magnetosphere Interaction (S_AO4) – Study the diurnal variations and magnetic control of the ionosphere of Saturn.
- Saturn Formation and Evolution (S_AO5) – Provide observational constraints (gas composition, isotope ratios, heat flux, ...) on scenarios for the formation and the evolution of Saturn.
- Saturn Lightning Sources and Morphology (S_AO6) – Investigate the sources and the morphology of Saturn lightning (Saturn electrostatic discharges (SEDs), lightning whistlers).

### *Saturn CSM Traceability Matrix objectives (see Saturn Discipline Report)*

- Seasonal Variations (SC1a) – Observe seasonal variations in temperature, clouds, and composition in three spatial dimensions.
- Saturn's Winds (SC1b) – Observe seasonal changes in the winds at all accessible altitudes coupled with simultaneous observations of clouds, temperatures, composition, and lightning.
- Aurorae, Chemistry, and Upper Atmosphere (SC2a) – Observe the magnetosphere, ionosphere, and aurora as they change on all time scales—minutes to years—and are affected by seasonal and solar cycle forcing.
- Saturn's Rotation Rate (SN1a) – Determine Saturn's rotation rate and internal structure despite the planet's unexpected high degree of axisymmetry.
- 2010–2011 Great Storm (SN1b) – Observe the aftermath of the 2010–2011 storm. Study the life cycles of Saturn's newly discovered atmospheric waves, south polar hurricane, and rediscovered north polar hexagon.
- Saturn Trace Gases (SN1c) – Measure the spatial and temporal variability of trace gases and isotopes.
- Saturn Storms and Lightning (SN2a) – Monitor the planet for new storms and respond with new observations when the new storms occur.

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### *Rings AO objectives (see Rings Discipline Report)*

- Ring Structure and Dynamics (R_AO1) – Study configuration of the rings and dynamical processes (gravitational, viscous, erosional, and electromagnetic) responsible for ring structure.
- Ring Particle Composition and Size (R_AO2) – Map composition and size distribution of ring material.
- Ring-Satellite Interaction (R_AO3) – Investigate interrelation of rings and satellites, including embedded satellites.
- Dust and Meteoroid Distribution (R_AO4) – Determine dust and meteoroid distribution both in the vicinity of the rings and in interplanetary space.
- Ring Magnetosphere-Ionosphere Interactions (R_AO5) – Study interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere.

### *Rings CSM Traceability Matrix objectives (see Rings Discipline Report)*

- Changing Rings (RC1a) – Determine the seasonal variation of key ring properties and the microscale properties of ring structure, by observing at the seasonally maximum opening angle of the rings near solstice.
- Ring Temporal Variability (RC1b) – Determine the temporal variability of ring structure on all timescales up to decadal for regions including Encke gap, D-ring, F-ring, and ring edges by substantially increasing the cadence and time baseline of observations.
- F-Ring (RC2a) – Focus on F-ring structure, and distribution of associated moonlets or clumps, as sparse observations show clumps, arcs, and possibly transient objects appearing and disappearing.
- Ring Age and Origin (RN1a) – Constrain the origin and age of the rings by direct determination of the ring mass, and of the composition of ring ejecta trapped on field lines.
- Ring Composition (RN1b) – Determine the composition of the close-in "ringmoons" as targets of opportunity.
- Ring Structure (RN1c) – Determine structural and compositional variations at high resolution across selected ring features of greatest interest, using remote and in situ observations.
- Ring Microstructure (RN2a) – Conduct in-depth studies of ring microstructure such as self-gravity wakes, which permeate the rings.
- New Ring Structures (RN2b) – Perform focused studies of the evolution of newly discovered "propeller" objects.

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### *MAPS AO objectives (see MAPS Discipline Report)*

- Saturn Magnetic Field Configuration and SKR (M_AO1) – Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of Saturn kilometric radiation (SKR).
- Magnetosphere Charged Particles (M_AO2) – Determine current systems, composition, sources, and sinks of magnetosphere charged particles.
- Magnetosphere Wave-Particle Interactions (M_AO3) – Investigate wave-particle interactions and dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interactions with the solar wind, the satellites, and the rings.
- Magnetosphere and Solar Interactions with Titan (M_AO4) – Study the effect of Titan's interaction with the solar wind and magnetospheric plasma.
- Plasma Interactions with Titan's Atmosphere and Ionosphere (M_AO5) – Investigate interactions of Titan's atmosphere and exosphere with the surrounding plasma.

### *MAPS CSM Traceability Matrix objectives (see MAPS Discipline Report)*

- Enceladus Plume Variability (MC1a) – Determine the temporal variability of Enceladus' plumes.
- Seasonal and Solar Cycle Variations (MC1b) – Observe Saturn's magnetosphere over a solar cycle, from one solar minimum to the next.
- Titan's Ionosphere (MC2a) – Observe seasonal variation of Titan's ionosphere, from one solstice to the next.
- Magnetotail (MN1a) – Determine the dynamics of Saturn's magnetotail.
- Saturn's Ionosphere and Radiation Belts (MN1b) – Conduct in situ studies of Saturn's ionosphere and inner radiation belt.
- Magntosphere Periodicities (MN1c) – Investigate magnetospheric periodicities, their coupling to the ionosphere, and how the SKR periods are imposed from close to the planet (3–5 Rs) out to the deep tail.
- Ionosphere and Ring Coupling (MN2a) – Determine the coupling between Saturn's rings and ionosphere.

### *Cruise Science AO objectives*

- Cruise Interstellar Ion Composition (C_AO1) – Extend the sensitivity of composition measurements of interstellar ions by approximately three orders of magnitude.
- Cruise Solar Wind Investigations (C_AO2) – Investigate the behavior of the solar wind during solar minimum, for comparison with earlier Galileo and Ulysses measurements.

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- Cruise Gravitational Wave Searches (C_AO3) – Extend spacecraft searches for gravitational waves.
- Cruise Interplanetary Dust Studies (C_AO4) – Extend studies of interplanetary dust to the orbit of Saturn.
- Cruise Planetary and Stellar Internal Oscillations (C_AO5) – Attempt to detect internal oscillations of Saturn, Jupiter, and some stars.

### *Jupiter Flyby AO objectives*

- Jupiter and Satellite Studies (J_AO1) – Extend the time for studies of atmospheric dynamics and variable satellite phenomena, specifically Io volcanism, beyond the period accessible to the Galileo nominal mission.
- Jupiter Global Atmospheric Structure and Composition (J_AO2) – Infer global atmospheric thermal structure and composition with instrumentation not carried by the Galileo orbiter, complementing the local in situ measurements of the Galileo probe.
- Jupiter Magnetospheric Studies (J_AO3) – Explore the dusk side of the magnetosphere and intermediate regions of the magnetotail unvisited by previous spacecraft.
- Jupiter Io Torus (J_AO4) – Obtain the first high-resolution images of the Io torus.

### *Venus Flyby AO objectives*

- N/A – There were no specific Venus science objectives called out in the Announcement of Opportunity. It was, however, an opportunity to calibrate and gauge the performance of instruments and test spacecraft functionality.

### *Asteroid Flyby AO objectives*

- Asteroid Flyby Investigation (A_AO1) – Investigate an asteroid not seen by previous missions, possibly a new class of asteroid, thereby adding important new information to the study of asteroids.
  - On January 23, 2000, observations by ISS, VIMS, and UVIS of the distant (1,634,000 km) asteroid 2685 Masursky were conducted. No papers or abstracts were written on the observation.
- Asteroid Global Characteristics (A_AO2) – Characterize global properties, determine composition and morphology of the surface, investigate properties of the regolith.
  - On January 23, 2000, observations by ISS, VIMS, and UVIS of the distant (1,634,000 km) asteroid 2685 Masursky were conducted. No papers or abstracts were written on the observation.

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## Project Science Assessment

Overall, the Cassini-Huygens mission was a tremendous success, accomplishing or exceeding almost all of the science objectives defined in the Cassini and Huygens AOs and in the Cassini Solstice Mission Traceability Matrices. Tables 3-7, 3-8, and 3-9 contain color-coded assessments of the science objectives for the Cassini-Huygens mission. If a science objective was accomplished or exceeded, its box is colored green. The rare exceptions, which are colored yellow or lime green, are instances where an objective was only partially accomplished. A full explanation of why it was not met is included in each yellow or lime green box.

Overall, the Cassini-Huygens mission was a tremendous success, accomplishing or exceeding almost all of the science objectives defined in the Cassini and Huygens AOs and in the Cassini Solstice Mission Traceability Matrices.

The project science assessments shown in Tables 3-7, 3-8, and 3-9 are a compilation of each discipline assessment and Huygens probe assessment. Table 3-7 includes the science assessments for the Icy Satellites, Titan, and Enceladus disciplines. Table 3-8 includes the science assessments for Saturn, Rings, and MAPS disciplines, while Table 3-9 includes the science assessments for Cruise and Jupiter science.

Future analysis of Cassini data may result in some unmet objectives being fully met. For example, at the writing of this report, Saturn's internal rotation rate could not be determined from the magnetometer data taken during Cassini's Grand Finale orbits at the end of the mission. The offset between Saturn's rotation axis and magnetic field axis appears to be too small to provide an estimate of Saturn's internal rotation rate. However, a paper by Mankovich et al. [2019] uses Saturn-driven waves detected in the main rings (kronoseismology) to determine an internal rotation rate for Saturn. Future analysis of Cassini data may provide additional information on Saturn's internal rotation rate. For more details on the specifics of the science assessments for each science objective, please see the discipline and team reports in Section 3, which also include their own color-coded science assessment tables.

**Table 3-7. Project Science Assessment (1 of 3 tables): Icy Satellites, Titan disciplines and Huygens.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini & Huygens Science Objectives | | |
|---|---|---|
| **Icy Satellites** | **Titan** | **Huygens** |
| **Prime Mission AO Objectives** | | |
| **Icy Satellite Geology and History (I_AO1)** - Determine the general characteristics and geological histories of the satellites. | **Titan Atmospheric Formation and Evolution (T_AO1)** - Determine abundances of atmospheric constituents (including any noble gases), establish isotope ratios for abundant elements, constrain scenarios of formation and evolution of Titan and its atmosphere. | **Titan Atmospheric Formation and Evolution (H_AO1)** - Determine abundances of atmospheric constituents (including any noble gases); establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere. |

**Table 3-7. Project Science Assessment (1 of 3 tables): Icy Satellites, Titan disciplines and Huygens.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini & Huygens Science Objectives | | |
|---|---|---|
| **Icy Satellites** | **Titan** | **Huygens** |
| **Icy Satellite Surface and Crustal Modifications (I_AO2)** - Define the mechanisms of crustal and surface modifications, both external and internal. | **Titan Atmospheric Composition and Distribution (T_AO2)** - Observe vertical and horizontal distributions of trace gases, search for more complex organic molecules, investigate energy sources for atmospheric chemistry, model the photochemistry of the stratosphere, study formation and composition of aerosols. | **Titan Atmospheric Composition and Distribution (H_AO2)** - Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photochemistry of the stratosphere; study formation and composition of aerosols.<br>*Note: This box is not green because the very low concentrations of aerosols collected by ACP limited the results to simple species, rather than complex hydrocarbon hazes.* |
| **Icy Satellite Surface Composition (I_AO3)** - Investigate the compositions and distributions of surface materials, particularly dark, organic rich materials and low melting point condensed volatiles. | **Titan Meteorology (T_AO3)** - Measure winds and global temperatures; investigate cloud physics, general circulation, and seasonal effects in Titan's atmosphere; search for lightning discharges. | **Titan Meteorology (H_AO3)** - Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges. |
| **Icy Satellite Interior Properties (I_AO4)** - Constrain models of the satellites' bulk compositions and internal structures. | **Titan Surface Characteristics and Internal Structure (T_AO4)** - Determine the physical state, topography, and composition of the surface; infer the internal structure of the satellite.<br>*Note: This box is not green because "Some work was done, but more work remains for future missions."* | **Titan Surface Characteristics and Internal Structure (H_AO4)** - Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite. |
| **Icy Satellite Magnetosphere and Ring Interactions (I_AO5)** - Investigate interactions with the magnetosphere and ring systems and possible gas injections into the magnetosphere. | **Titan Upper Atmosphere (T_AO5)** - Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn. | **Titan Upper Atmosphere (H_AO5)** - Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn. |
| **Science Traceability Matrix** | | |
| **Enceladus Seasonal Changes (IC1a)** - Identify long-term secular and seasonal changes at Enceladus, through observations of the south polar region, jets, and plumes. | **Titan's Great Seas (TC1a)** - Determine seasonal changes in the methane-hydrocarbon hydrological cycle: of lakes, clouds, aerosols, and their seasonal transport. | |
| **Enceladus Ocean (IN1a)** - Determine the presence of an ocean at Enceladus as inferred from induced magnetic field and plume composition, search for possible anomalies in the internal structure of Enceladus as associated with plume sources, and constrain the mechanisms driving the endogenic activity by in situ observations and remote sensing. | **Titan's Global Seasons (TC1b)** - Determine seasonal changes in the high-latitude atmosphere, specifically the temperature structure and formation and breakup of the winter polar vortex. | |

**Table 3-7. Project Science Assessment (1 of 3 tables): Icy Satellites, Titan disciplines and Huygens.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini & Huygens Science Objectives | | |
|---|---|---|
| **Icy Satellites** | **Titan** | **Huygens** |
| **Mid-sized Satellites (IN1b)** - Complete the comparative study of Saturn's mid-sized satellites, their geological and cratering histories, and interactions with the Saturn system, with remote sensing of Mimas at the highest resolution possible in order to understand the mechanisms behind its unique thermal properties discovered by Cassini. | **Titan-Magnetosphere Interaction (TC2a)** - Observe Titan's plasma interaction as it goes from south to north of Saturn's solar-wind-warped magnetodisk from one solstice to the next. | |
| **Dione (IN1c)** - Determine whether Dione exhibits evidence for low-level activity, now or in recent geological time.<br>*Note: This box is not green because extensive data were gathered, but the current results are still ambiguous. No current activity was detected.* | **Titan's Surface (TN1a)** - Determine the types, composition, distribution, and ages, of surface units and materials, most notably lakes (i.e., filled vs. dry & depth; liquid vs. solid & composition; polar vs. other latitudes & lake basin origin). | |
| **Rhea (IN2a)** - Determine whether there is ring material orbiting Rhea, and if so, what its spatial and particle size distribution is. | **Titan's Interior Ocean (TN1b)** - Determine internal and crustal structure: Liquid mantle, crustal mass distribution, rotational state of the surface with time, intrinsic and/or internal induced magnetic field.<br>*Note: This box is not green because 1) Cassini only studied a few crustal structures locally and crustal viscosity was not determined by data taken, and 2) induced magnetic fields were difficult to determine due to ionospheric currents.* | |
| **Tethys (IN2b)** - Determine whether Tethys contributes to the E-ring and the magnetospheric ion and neutral population.<br>*Note: From a CDA/icy dust perspective, this box is not green because during the Solstice Mission there were no close Tethys flybys to measure potential ejecta [Kempf, Beckmann, and Schmidt 2010]. For MAPS as a whole, enough data were obtained to determine that Tethys does not contribute to the E-ring and magnetospheric ion and neutral population [Burch et al. 2007; Khurana, Russell, and Dougherty 2008], yielding an overall yellow box.* | **Titan Atmospheric Composition (TN1c)** - Measure aerosol and heavy molecule layers and properties. | |
| **Satellite Interiors (IN2c)** - Determine the extent of differentiation and internal inhomogeneity within the icy satellites, especially Rhea and Dione. | **Titan Atmospheric Structure (TN2a)** - Resolve current inconsistencies in atmospheric density measurements (critical to a future Flagship mission). | |

**Table 3-7. Project Science Assessment (1 of 3 tables): Icy Satellites, Titan disciplines and Huygens.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini & Huygens Science Objectives | | |
|---|---|---|
| **Icy Satellites** | **Titan** | **Huygens** |
| **Small Moons (IN2d)** - Observe selected small satellites to quantify the movement of Enceladus material through the system, the history of satellite collisions/breakup, interaction with ring material as indicated by surface properties/composition, and cratering rates deep in the Saturnian system. | **Titan's Icy Shell (TN2b)** - Determine icy shell topography and viscosity. *Note: This box is not green because crustal viscosity could not be determined to date from data taken.* | |
| **Hyperion (IN2e)** - Understand the unusual appearance of Hyperion with remote sensing observations of the highest resolution possible. | **Titan Meteorology (TN2c)** - Determine the surface temperature distribution, cloud distribution, and tropospheric winds. | |
| **Iapetus (IN2f)** - Use remote sensing of Iapetus to test models for the albedo heterogeneity of the satellite. Quantify the effect of the newly-discovered Phoebe ring on the properties of Iapetus' surface. | | |

**Table 3-8. Project Science Assessment (2 of 3 tables): Saturn, Rings and MAPS disciplines.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini Science Objectives | | |
|---|---|---|
| **Saturn** | **Rings** | **MAPS** |
| **Prime Mission AO Objectives** | | |
| **Saturn Temperature, Clouds, Composition (S_AO1)** - Determine temperature field, cloud properties, and composition of the atmosphere of Saturn. | **Ring Structure and Dynamics (R_AO1)** - Study configuration of the rings and dynamical processes (gravitational, viscous, erosional, and electromagnetic) responsible for ring structure. | **Saturn Magnetic Field Configuration and SKR (M_AO1)** - Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of SKR. |
| **Saturn Winds and Weather (S_AO2)** - Measure the global wind field, including wave and eddy components; observe synoptic cloud features and processes. | **Ring Particle Composition and Size (R_AO2)** - Map composition and size distribution of ring material. | **Magnetosphere Charged Particles (M_AO2)** - Determine current systems, composition, sources, and sinks of magnetosphere charged particles. |
| **Saturn Interior Structure and Rotation (S_AO3)** - Infer the internal structure and rotation of the deep atmosphere. *Note: This box is not green because at the time of this report, Saturn's internal rotation rate could not be determined from the Grand Finale magnetic field data. Mankovich et al. [2019] may have finally determined the rotation rate from patterns related to kronoseismology in Saturn's rings, at which point this box would become green.* | **Ring-Satellite Interaction (R_AO3)** - Investigate interrelation of rings and satellites, including embedded satellites. | **Magnetosphere Wave-Particle Interactions (M_AO3)** - Investigate wave-particle interactions and dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interactions with the solar wind, the satellites, and the rings. |
| **Saturn Ionosphere-Magnetosphere Interaction (S_AO4)** - Study the diurnal variations and magnetic control of the ionosphere of Saturn. | **Dust and Meteoroid Distribution (R_AO4)** - Determine dust and meteoroid distribution both in the vicinity of the rings and in interplanetary space. | **Magnetosphere and Solar Interactions with Titan (M_AO4)** - Study the effect of Titan's interaction with the solar wind and magnetospheric plasma. |

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**Table 3-8. Project Science Assessment (2 of 3 tables): Saturn, Rings and MAPS disciplines.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini Science Objectives | | |
|---|---|---|
| **Saturn** | **Rings** | **MAPS** |
| **Saturn Formation and Evolution (S_AO5)** - Provide observational constraints (gas composition, isotope ratios, heat flux, ...) on scenarios for the formation and the evolution of Saturn. | **Ring Magnetosphere-Ionosphere Interactions (R_AO5)** - Study interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere. | **Plasma Interactions with Titan's Atmosphere and Ionosphere (M_AO5)** - Investigate interactions of Titan's atmosphere and exosphere with the surrounding plasma. |
| **Saturn Lightning Sources and Morphology (S_AO6)** - Investigate the sources and the morphology of Saturn lightning (Saturn electrostatic discharges (SEDs), lightning whistlers). | | |
| **Science Traceability Matrix** | | |
| **Seasonal Variations (SC1a)** - Observe seasonal variations in temperature, clouds, and composition in three spatial dimensions. | **Changing Rings (RC1a)** - Determine the seasonal variation of key ring properties and the microscale properties of ring structure, by observing at the seasonally maximum opening angle of the rings near solstice. | **Enceladus Plume Variability (MC1a)** - Determine the temporal variability of Enceladus' plumes. |
| **Saturn's Winds (SC1b)** - Observe seasonal changes in the winds at all accessible altitudes coupled with simultaneous observations of clouds, temperatures, composition, and lightning. | **Ring Temporal Variability (RC1b)** - Determine the temporal variability of ring structure on all timescales up to decadal for regions including Encke gap, D-ring, F-ring, and ring edges by substantially increasing the cadence and time baseline of observations. | **Seasonal and Solar Cycle Variations (MC1b)** - Observe Saturn's magnetosphere over a solar cycle, from one solar minimum to the next. |
| **Aurorae, Chemistry, and Upper Atmosphere (SC2a)** - Observe the magnetosphere, ionosphere, and aurora as they change on all time scales—minutes to years—and are affected by seasonal and solar cycle forcing. | **F-ring (RC2a)** - Focus on F-ring structure, and distribution of associated moonlets or clumps, as sparse observations show clumps, arcs, and possibly transient objects appearing and disappearing. | **Titan's Ionosphere (MC2a)** - Observe seasonal variation of Titan's ionosphere, from one solstice to the next. |
| **Saturn's Rotation Rate (SN1a)** - Determine Saturn's rotation rate and internal structure despite the planet's unexpected high degree of axisymmetry. | **Ring Age and Origin (RN1a)** - Constrain the origin and age of the rings by direct determination of the ring mass, and of the composition of ring ejecta trapped on field lines. | **Magnetotail (MN1a)** - Determine the dynamics of Saturn's magnetotail. |
| **2010—2011 Great Storm (SN1b)** - Observe the aftermath of the 2010—2011 storm. Study the life cycles of Saturn's newly discovered atmospheric waves, south polar hurricane, and rediscovered north polar hexagon. | **Ring Composition (RN1b)** - Determine the composition of the close-in "ringmoons" as targets of opportunity. | **Saturn's Ionosphere and Radiation Belts (MN1b)** - Conduct in situ studies of Saturn's ionosphere and inner radiation belt. |

**Table 3-8. Project Science Assessment (2 of 3 tables): Saturn, Rings and MAPS disciplines.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini Science Objectives | | |
|---|---|---|
| **Saturn** | **Rings** | **MAPS** |
| **Saturn Trace Gases (SN1c)** - Measure the spatial and temporal variability of trace gases and isotopes. | **Ring Structure (RN1c)** - Determine structural and compositional variations at high resolution across selected ring features of greatest interest, using remote and in situ observations. | **Magntosphere Periodicities (MN1c)** - Investigate magnetospheric periodicities, their coupling to the ionosphere, and how the SKR periods are imposed from close to the planet (3–5 $R_S$) out to the deep tail. *Note: This box is not green because at the time of this report, Saturn's internal rotation rate could not be determined from the Grand Finale magnetic field data. Mankovich et al. [2019] may have finally determined the rotation rate from patterns related to kronoseismology in Saturn's rings, at which point this box would become green.* |
| **Saturn Storms and Lightning (SN2a)** - Monitor the planet for new storms and respond with new observations when the new storms occur. | **Ring Microstructure (RN2a)** - Conduct in-depth studies of ring microstructure such as self-gravity wakes, which permeate the rings. | Ionosphere and Ring Coupling (MN2a) - Determine the coupling between Saturn's rings and ionosphere. |
| | **Ring Microstructure (RN2a)** - Conduct in-depth studies of ring microstructure such as self-gravity wakes, which permeate the rings. | |

**Table 3-9. Project Science Assessment (3 of 3 tables): Cruise Science and Jupiter.**

Table Legend: Green: Fully Accomplished Yellow: Partially Accomplished

| Cassini Science Cruise & Jupiter Flyby Objectives | |
|---|---|
| **Cruise Science** | **Jupiter** |
| **Cruise Interstellar Ion Composition (C_AO1)** - Extend the sensitivity of composition measurements of interstellar ions by approximately three orders of magnitude. | **Jupiter and Satellite Studies (J_AO1)** - Extend the time for studies of atmospheric dynamics and variable satellite phenomena, specifically Io volcanism, beyond the period accessible to the Galileo nominal mission. |
| **Cruise Solar Wind Investigations (C_AO2)** - Investigate the behavior of the solar wind during solar minimum, for comparison with earlier Galileo and Ulysses measurements. | **Jupiter Global Atmospheric Structure and Composition (J_AO2)** - Infer global atmospheric thermal structure and composition with instrumentation not carried by the Galileo Orbiter, complementing the local in situ measurements of the Galileo Probe. |
| **Cruise Gravitational Wave Searches (C_AO3)** - Extend spacecraft searches for gravitational waves. | **Jupiter Magnetospheric Studies (J_AO3)** - Explore the dusk side of the magnetosphere and intermediate regions of the magnetotail unvisited by previous spacecraft. |
| **Cruise Interplanetary Dust Studies (C_AO4)** - Extend studies of interplanetary dust to the orbit of Saturn. | **Jupiter Io Torus (J_AO4)** - Obtain the first high-resolution images of the Io torus. |
| **Cruise Planetary and Stellar Internal Oscillations (C_AO5)** - Attempt to detect internal oscillations of Saturn, Jupiter, and some stars. | |

As can be seen in Tables 3-7, 3-8, and 3-9, the Cassini-Huygens mission was extremely successful in accomplishing its scientific objectives.

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# Cassini's Top Science Highlights

Many of Cassini's findings revolutionized our understanding of the Saturn system. Some of Cassini's most surprising scientific discoveries came from encounters with Saturn's intriguing moons. Enceladus harbors a salty, liquid water ocean beneath its icy crust that is the source for icy jets and huge plume spewing from fractures at its south pole. On giant Titan, methane rain carves river channels and fills lakes and seas with hydrocarbons, mixed with complex prebiotic chemicals that form in its atmosphere and rain to the surface. From Huygens probe data it was determined that Titan, too, has an internal liquid water ocean. Some of Cassini's other amazing findings include a myriad of three-dimensional structures in the dynamic rings driven by interactions with Saturn's moons and interior; a giant Saturn storm that circled the entire planet for most of 2011, while a long-lived hexagonal jet stream discovered by Voyager in 1981 continues to encircle the north polar region. Cassini solved the mystery of Iapetus' dual bright-dark surface, and the true rotation rate of Saturn's interior. During the final year of the mission, moving closer to Saturn than ever before, provided an astonishing array of discoveries about the interior of Saturn, its rings and tiny ringmoons, and the gap between the rings and the planet. This section highlights some of Cassini's top scientific discoveries. Additional details about each of them can be found in the discipline and instrument team reports in Section 3 and in Spilker [2019].

## Enceladus: Discovery of an Ocean World

The discovery of Enceladus' massive plume spewing into space was such a surprise that mission designers completely reshaped the mission to get a more detailed look, adding 20 more close Enceladus flybys, for a total of 23 during the mission. The discovery became even more important when Cassini found evidence of water vapor and water ice in the plume. Life as we know it relies on water, so the search for life suddenly extended to this small, bright moon. The discovery of a subsurface ocean makes Enceladus one of the most exciting science destinations in our solar system.

Prior to Cassini's arrival, Enceladus, a small moon only about 500 km across, was puzzling because of its very bright surface. As the brightest moon in our solar system, it reflects almost 90% of the sunlight it receives. During Cassini's early flybys, images of the moon (Figure 3-7) revealed a system of extensive cracks and large regions completely devoid of craters. The south polar region contains large tectonic features, is devoid of craters, and is the youngest surface on Enceladus. It includes a system of four nearly parallel fractures, nicknamed "tiger stripes," that are centered near the pole [Helfenstein 2010]. Each "tiger stripe" is about 130 km long and 2–4 km wide. They are separated from each other by approximately 35 km.

Activity on Enceladus was first detected by Cassini's magnetometer as a deflection of Saturn's magnetic field [Dougherty et al. 2006]. During a close targeted flyby in 2005, Cassini's thermal infrared spectrometer discovered a hot spot centered near the South Pole [Spencer et al. 2006]. The four tiger stripe fractures were the warmest regions—more than 100 degrees Celsius warmer than the surrounding areas [Howett et al. 2011]—and were the source of an immense ice plume

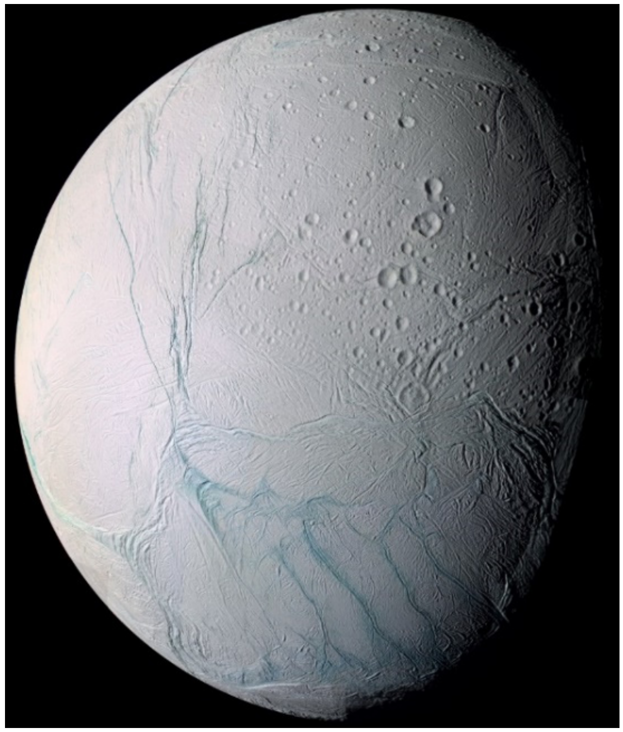

**Figure 3-7. Enceladus' bright surface, with very few craters, indicates a young surface. Four bluish "tiger stripe" fractures at the South Pole are the source of the icy jets and plume.**

imaged by Cassini's camera [Porco et al. 2006]. The giant cryovolcanic plume of water vapor and ice grains is fed by both discrete jets [Porco, DiNino, and Nimmo 2014] and curtains of material [Spitale et al. 2015] originating inside each tiger stripe (Figure 3-8). The localized jets in the tiger stripes are the warmest regions on the moon [Spencer and Nimmo 2013; Goguen et al. 2013]. The unexpected discovery of Enceladus' extensive water vapor and ice particle plume was such a surprise that future mission phases were reshaped to capitalize on this discovery. Cassini ultimately flew through the Enceladus plume seven times, directly sampling its gas and icy particles.

The lack of impact craters in the tiger stripe region demonstrates that it is a geologically fresh surface that is constantly renewing itself. A fair fraction of the plume material eventually re-impacts Enceladus but some of the smallest grains are the source of the tenuous, distended E-ring [Spencer et al. 2006; Kempf, Beckmann, and Schmidt 2010; Mitchell, Porco, and Weiss 2015], which is densest at the orbit of Enceladus and spreads throughout the system. The E-ring interacts with the inner moons, coating one side with bright, fresh material. Cassini discovered that the source of the plume is a global liquid water ocean beneath Enceladus' crust [Iess et al. 2014; Thomas et al. 2016]. The ocean is about 10 km deep beneath an ice shell that is about 26–31 km thick, and perhaps considerably thinner, as thin as 5 km, in the south polar region.

In addition to water vapor [Hansen et al. 2006], Cassini's INMS discovered that the plume gasses contain carbon dioxide and simple hydrocarbons such as methane, propane, and acetylene [Waite et al. 2009; Waite et al. 2017]. During Cassini's closest dive through the plume in 2015,

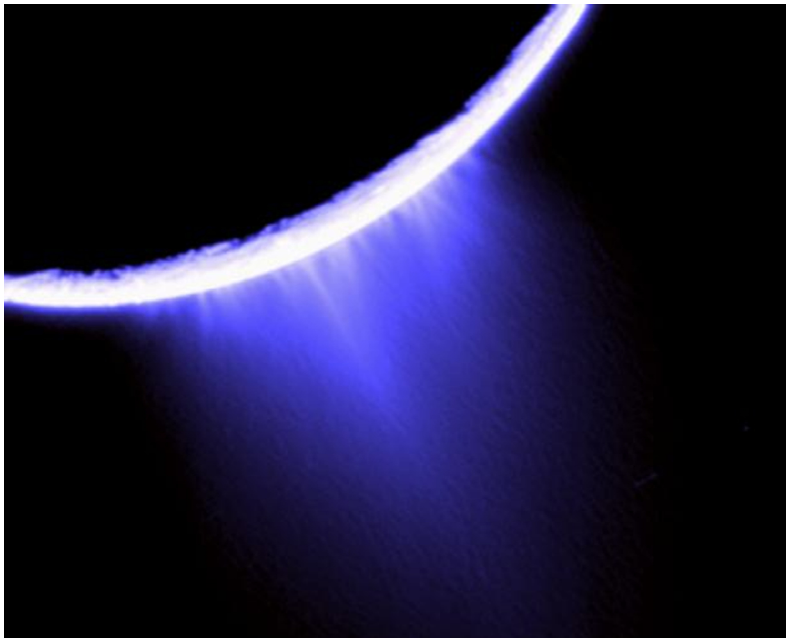

**Figure 3-8. Icy jets shoot from Enceladus' South Pole. Jets form a ghostly plume of particles, some fall back to the moon and others create the E-ring. This false-color image was taken by NASA's Cassini spacecraft.**

INMS discovered molecular hydrogen ($H_2$) [Waite et al. 2017]. Cassini's CDA found icy particles as well as salt-rich ice grains containing sodium and potassium that are probably frozen droplets from the underground salty ocean [Postberg et al. 2009; Postberg et al. 2011; Glein, Baross, and Waite 2015]. CDA also discovered tiny grains of silica, less than 10 nanometers in size, originating from Enceladus' ocean [Hsu et al. 2015]. These tiny silica grains most likely condensed from hot water spewing from hydrothermal vents on Enceladus' seafloor. The excess hydrogen discovered by INMS could also be coming from the hydrothermal vents. CDA and INMS also detected evidence for large organic fragments, indicative of complex organic molecules that are created in chemical processes, perhaps including those related to life [Postberg et al. 2018]. The source of energy for the hydrothermal activity on Enceladus is tidal interactions among Enceladus, Dione, and Saturn [Tobie, Cadek, and Sotin 2008]. With liquid water, an energy source, and organic molecules, the subsurface ocean of Enceladus could harbor the ingredients for primitive life. The Cassini orbiter did not carry the instruments needed to detect life so that goal remains for a future mission. Enceladus and the other icy moons of Saturn are discussed in detail in the book edited by Schenk et al. [2018]. For more details about Enceladus science, see the Icy Satellite report and the team reports.

## Titan: Earth-like World with Rain, Rivers, Lakes and Seas, Global Ocean, and Prebiotic Chemistry

Titan is the largest moon in the Saturn system, slightly larger than the planet Mercury, and the only moon in our solar system with a dense atmosphere. Titan is also the only body other than Earth that displays clear evidence for surface liquids: liquid hydrocarbons. Titan's atmosphere is mostly nitrogen with some methane and a haze layer of organics that give Titan its orange appearance. Key Titan results can be found in the books, *Titan: Interior, surface, atmosphere, and space environment* [Müller-Wodarg et al. 2014] and *Titan from Cassini-Huygens* [Brown, Lebreton, and Waite 2009].

Titan has many geologic processes similar to that of Earth. These processes generate methane rains, which build river channels and form lakes and seas containing liquid methane and ethane. Titan's atmosphere is teaming with a variety of molecules—the most chemically complex in the solar system. Beginning with sunlight and methane, ever more complex molecules form until they become large enough to form the smog that covers the giant moon. Nearer the surface, methane, ethane, and other organics condense and fall to the surface where likely other prebiotic chemistry can take place.

Cassini revealed an array of complex hydrocarbons in Titan's atmosphere, created as methane gas is broken apart by sunlight in the upper atmosphere, generating active chemistry [Waite et al. 2007] and a link to haze formation [Lavvas et al. 2013]. The mechanism by which methane is replenished remains a mystery. Over the course of the mission, methane rainfall darkened parts of Titan's surface [Turtle et al. 2009; Turtle et al. 2011], and methane clouds formed and dissipated [Rodriguez et al. 2009]. As the seasons changed, the evolution and breakup of Titan's northern winter polar vortex and the early formation of Titan's southern winter polar vortex were observed [Vinatier et al. 2015; Achterberg et al. 2011]. The polar vortices appear to be tilted by a few degrees relative to the rotational pole of Titan, and the entire stratosphere is also tilted by several degrees [Achterberg et al. 2008].

The surface of Titan was examined from orbit using radar and imaging at both visible and infrared wavelengths, which showed that Titan has many geologic processes reminiscent of those on Earth. Radar wavelengths can pierce the haze, allowing us to see Titan's surface. These processes generate methane clouds and rain, build river channels, form lakes and seas (Figure 3-9) containing liquid methane and ethane, form complex atmospheric hydrocarbons, and generate dunes of hydrocarbon particles. Cassini's studies revealed Titan to be remarkably like a prebiotic Earth. On Titan, methane plays the role of water on Earth and water ice is a key ingredient of the rocky soil. Titan's methane cycle is analogous to Earth's hydrologic cycle, but at temperatures about 200 K lower.

Titan's surface consists of broad regions of light and dark terrain. Some of the dark, equatorial regions generally consist of long, linear dunes [Radebaugh et al. 2008]. Titan's lakes and seas are confined primarily to the polar regions. In the south polar region, one lake, Ontario Lacus, was seen by Cassini while the north polar region small lakes, and large seas about the size of the Great Lakes, abound [Stofan et al. 2007]. A specular reflection observed by VIMS definitively verified that the dark lake regions contain liquid [Stephan et al. 2010]. For more details about Titan, see the Titan report and team reports in Sections 3.1 and 3.2.

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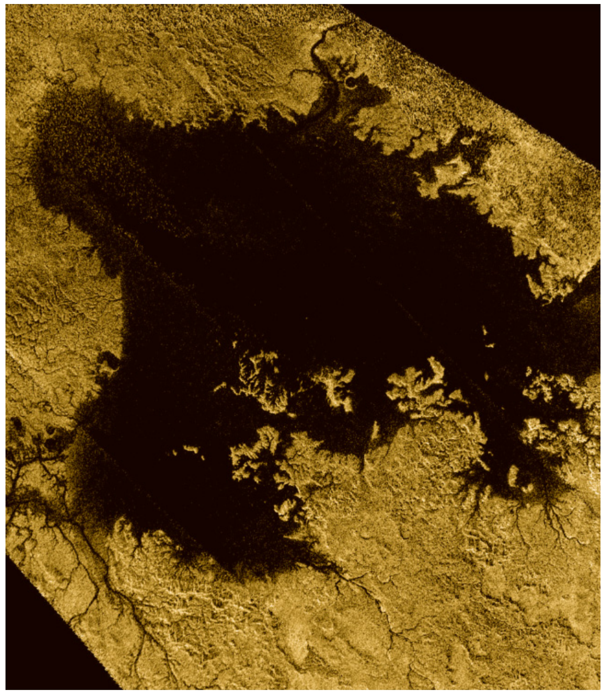

**Figure 3-9. Radar view of Titan sea Ligeia Mare with river channels flowing into it. Ligeia Mare is 50% larger than Earth's Lake Superior and ~500 feet deep, also similar to the Great Lakes.**

## Huygens Probe: First Landing on an Outer Solar System Moon (Titan)

The Huygens probe became the first human-made object to land on Titan. Huygens was built and operated by ESA and was carried as a passenger on the Cassini spacecraft. Huygens separated from Cassini in December 2004 and landed on Titan three weeks later, on January 14, 2005.

Huygens's historic 2005 landing on Titan was the most distant in our solar system to date. The probe's descent revealed Titan to be remarkably like Earth before life evolved, with methane rain, erosion and drainage channels, and dry lake beds. An array of complex hydrocarbons was found in Titan's atmosphere, created by the break-up of methane high in the atmosphere.

Huygen's 2 hour 27 min parachuted descent provided the first in situ atmospheric profile of temperature, pressure, density, wind, and composition, as well as detailed images of the surface. The surface pressure was 1.47 times that on Earth [Fulchignoni et al. 2005]; super-rotating prograde, zonal winds peaked at 430 km hour$^{-1}$, much greater than Titan's equatorial rotation velocity [Bird et al. 2005]; and atmospheric composition included the noble gases argon, krypton, and xenon [Niemann et al. 2005], whereas nitrogen and methane were confirmed as the primary constituents [Niemann et al. 2010]. After landing, the GCMS measured an increase in abundance of methane gas as the relatively warm GCMS inlet heated Titan's surface [Niemann et al. 2005].

The Cassini spacecraft flew overhead and collected the Huygens data, including about 72 minutes on Titan's surface, before Huygen's link to Cassini was lost as Cassini set over the horizon. Huygens landed in a dry lakebed filled with rounded pebbles (Figure 3-10), near the Xanadu region, an equatorial area about the size of Australia. Images taken at about 10 km altitude captured dendritic erosional patterns on a hillside with very steep slopes. The rounded, smoothed pebbles at the landing site are evidence of fluid flow [Tomasko et al. 2005].

An overview of Huygens science can be found in Lebreton et al. [2009] and in the Huygens report.

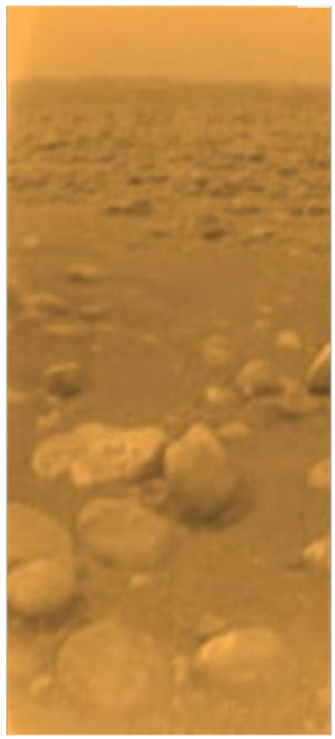

**Figure 3-10. Huygens image from the surface of Titan. This colored view was processed to add reflection spectral data, and gives a better indication of the actual color of the surface.**

## Iapetus: Mystery of the Dual, Bright-dark Surface of the Moon Solved

The origin of Iapetus's two-face, bright-dark surface has been a mystery for more than 300 years (Figure 3-11). The Cassini spacecraft solved the puzzle. Dark, reddish dust in Iapetus' orbital path is swept up and lands on the leading face of the moon. The dark areas absorb energy and become warmer, while uncontaminated areas remain cooler. The moon's long rotation period contributes to this yin-yang effect.

One hemisphere of Iapetus is as dark as charcoal while the other half is nearly as bright as snow. The reason for this light-dark dichotomy was not known prior to Cassini's arrival at Saturn. An Earth-orbiting infrared telescope discovered a very tenuous ring at the orbit of Phoebe [Verbiscer, Skrutskie, and Hamilton 2009], probably dust thrown off the moon by tiny meteor impacts. This dust is swept up by Iapetus as it orbits Saturn. The darkest side of the moon is centered exactly in the direction of motion of the satellite. A handful of small impact craters on the dark side punch through to bright material below, suggesting that the dark material is not very deep.

Cassini discovered a 20 km high ridge that circles most of the equator [Porco et al. 2005]. The ridge breaks up into mountains in some of the lowest albedo regions. The ridge must have been formed early in the history of Iapetus because it is heavily cratered and eroded. The surface of Iapetus is mainly water ice with small amounts of carbon dioxide, carbon, and complex organic molecules present.

**Figure 3-11. The dark surface of Iapetus and the dark, heavily cratered region called Cassini Regio are visible, along with the giant ridge that circles Iapetus's equator.**

## *Moons Mimas and Phoebe*

The Saturn system contains 62 known moons, many of them small, captured objects that are distant from Saturn and irregular in shape. Much closer to Saturn are 24 regular moons that probably formed from the same sub-nebula as Saturn. Some of these moons have strong interactions with the ring system, opening gaps and sculpting the rings. More information about Enceladus and the icy satellites can be found in Schenk et al. [2018].

Mimas is the innermost and smallest of the intermediate-sized moons with a diameter of 394 km. During a close flyby in February 2010 the infrared spectrometer discovered that the leading side of Mimas—the hemisphere that faces forward in the moon's orbit about Saturn—is about 15 degrees K colder than the other side [Howett et al. 2011]. This thermal anomaly, in the shape of "Pac-Man," is a result of a contrast in thermal inertia between the leading and trailing sides of Mimas. The leading face is altered by bombardment of highly energetic electrons. This bombardment increases the contact between regolith grains, decreases their porosity and increases thermal inertia [Schenk et al. 2011]. Models of Saturn's E-ring suggest that the side of

Mimas that faces away from the direction of motion should be preferentially coated by particles from the E-ring. Mimas' exceptionally high reflectivity (it is the second most reflective moon in the solar system) supports this hypothesis. Water ice is the primary compound detected on its surface. Its heavily cratered appearance argues against current activity on the moon.

Two weeks before Saturn Orbit Insertion (SOI), Cassini-Huygens flew close to Phoebe, the largest outer irregular moon of Saturn. Phoebe moves in an inclined, retrograde orbit that is 13 million kilometers from Saturn. It is covered with impact craters that were probably created by collisions with smaller outer moons. Some of the craters contain icy patches and layered structures; others have unusual conical shapes. Phoebe reflects only a few percent of the sunlight that falls on it, about the same as that reflected by the dark regions of Earth's moon. In addition to water ice, its surface is composed of carbon and carbon dioxide [Clark et al. 2005]. The presence of carbon and the fact that its density is higher than that of the other medium-sized moons of Saturn suggest that Phoebe was formed near the edge of the solar system and migrated inward to be captured by Saturn [Johnson and Lunine 2005]. Phoebe may have originated in the Kuiper Belt, the reservoir of ice/rock bodies that dwell beyond the orbit of Neptune and that may provide clues to the architecture of the early solar system and its subsequent evolution.

### *Discovery of seven small moons*

Cassini discovered seven small moons in the inner Saturn system [Thomas et al. 2016]. Pallene and Aegaeon are associated with diffuse, dusty rings, and Anthe and Methone are associated with ring arcs. A tiny moon, Daphnis, orbits in the Keeler gap and may help to keep it clear. An even smaller moon causes propeller-like structures in a ring of Saturn (S/2009 S). A new moon, Aegaeon, was discovered inside Saturn's G-ring [Hedman et al. 2010]. Another Cassini discovery is the moon Polydeuces, which moves in a gravitationally stable zone in Dione's orbit known as the Lagrangian point.

Prior to Cassini, Saturn already had a unique family of small satellites, including the co-orbitals Janus and Epimetheus, which switch orbits every four years and appear to have been one body until their violent separation. Other previously known moons include the F-ring shepherds, Prometheus and Pandora, as well as Atlas, orbiting just outside the A-ring edge, and Pan, which clears the Encke gap.

## Saturn's Rings: Revealed as Active and Dynamic—A Laboratory for How Planets Form

Cassini's 13 years in orbit made it possible to watch changes in Saturn's dynamic ring system. The spacecraft discovered propeller-like formations, witnessed the possible birth of a new moon and observed what may be one of the most active, chaotic rings in our solar system, Saturn's F-ring.

Saturn's rings are both beautiful and complex, and the processes observed there provide a laboratory for how planets might form. Some of the highest resolution data on the rings were obtained at SOI in 2004. Tiny propellers and straw-like clumping in the strongest density wave peaks were first detected in the images from the SOI unlit ring scan. For more detailed summaries, see ring chapters in the books, *Saturn from Cassini-Huygens* [Dougherty, Esposito, and Krimigis 2009], and *Planetary Ring Systems: Properties, Structure, and Evolution* [Tiscareno and Murray 2018].

Some places in Saturn's rings were changing on very short timescales of weeks or months. Dozens of objects, 0.1–1 km in size, orbiting in the A-ring, changed their locations as they interacted with neighboring material. These unseen objects opened up tiny propeller-shaped gaps that were captured in the Cassini cameras and in stellar occultations of the rings [Tiscareno et al. 2010] (Figure 3-12). Cassini observed channels opening and closing in the F-ring, in response to close approaches by the tiny moon Prometheus [Murray et al. 2005]. Clumps and dusty jets appeared and disappeared in the F-ring core, excited by embedded moonlets and disturbed by objects with orbits eccentric enough to dive through the ring [Murray et al. 2008; Beurle et al. 2010]. Several new ringlets appeared during Cassini's 13 years in orbit [Hedman et al. 2009]. They were composed mostly of fine dust grains; one in the outer Cassini division was barely visible when Cassini arrived but was among the dustiest features in the rings by the end of the mission.

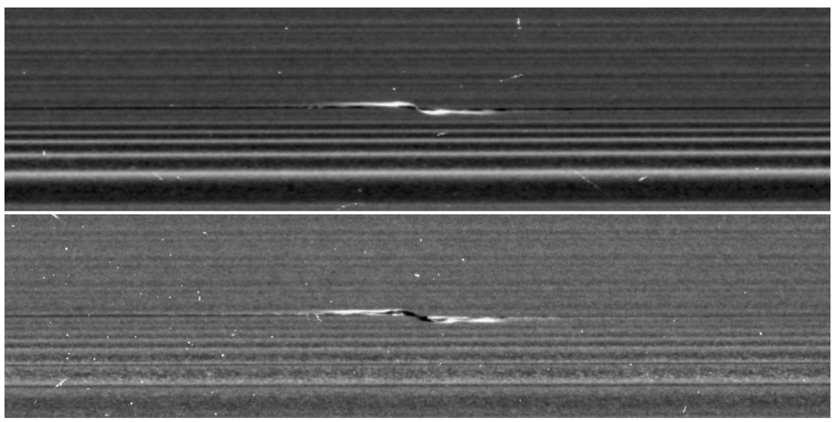

**Figure 3-12. Propeller structures are caused by embedded moonlets at their centers, and have much in common with baby planets embedded in protoplanetary disks. View of propeller Santos Dumont on the sunlit side of the rings (top panel) and unlit side of the rings (bottom panel).**

The ring particles in Saturn's main A- and B-rings are nearly pure water ice but show a strong ultraviolet absorption that varies in strength from place to place. A reddish color of varying intensity in the rings is deeper where the ice signature is strongest. The rings probably darken with time as they are polluted by meteoroid bombardment. The less massive C-ring and Cassini division look more polluted (redder) than the more massive A-ring and B-ring [Cuzzi et al. 2010].

Hundreds of stellar and radio occultations of the rings were obtained throughout the mission at a large variety of ring geometries, including some of the best-ever radio occultations during the Grand Finale as the radio signal was beamed through the rings while Cassini flew close to Saturn. Detailed horizontal and vertical structure in the rings was revealed at multiple wavelengths. They provided a detailed map of Saturn's rings, including three-dimensional measurements of tendril-like, ephemeral structures in the rings called self-gravity wakes [Colwell, Esposito, and Sremcevic 2006]. These transient gravitational instabilities form but are torn apart by Saturn's tides. Similar behavior in a protoplanetary disk might play a role in formation of planets in our own solar system and beyond. A different kind of microstructure, which behaves like self-gravity but is due more to viscous forces in the rings than self-gravity, can also be seen throughout the densest parts of the rings [Colwell et al. 2007].

Modeling of the damping behavior of dozens of spiral density and bending waves constrained the mass of most of Saturn's main rings [Tiscareno et al. 2007]. However, occultations were not able to directly probe the densest parts of the B-ring so its mass remained uncertain until gravity measurements in the Grand Finale orbits found that the total mass of the rings was less than all previous estimates, hinting at a young age for the rings [Iess et al. 2019].

## Vertical Structures in the Rings Imaged for the First Time

Once about every 15 years, the Sun shines on the edge of the ring plane and northern and southern sides of the rings receive little sunlight. Cassini measured the long shadows from this rare event to determine the heights of structures within the rings.

Many new discoveries were made during equinox in August 2009, the time when the Sun was edge-on to the rings. Once every half Saturn year, the ring plane aligns with the center of the Sun, and for a brief time, the northern and southern sides of the rings receive essentially no sunlight. Vertically extended objects cast long shadows on the rings that provided a measurement of the height of these ring structures. During this unique time, Cassini observed long shadows up to 2.5 km long (Figure 3-13) created by objects larger than the 5-meter vertical thickness of the rings. They included shadows from towering km-sized objects near the outer edge of the B-ring, and the vertical extent of edge waves in the Keeler gap created by the tiny moon Daphnis [Tiscareno and Murray 2018]. The rings also cooled to their lowest temperatures, heated for a few days only by Saturn shine [Spilker, Ferrari, and Morishima 2013].

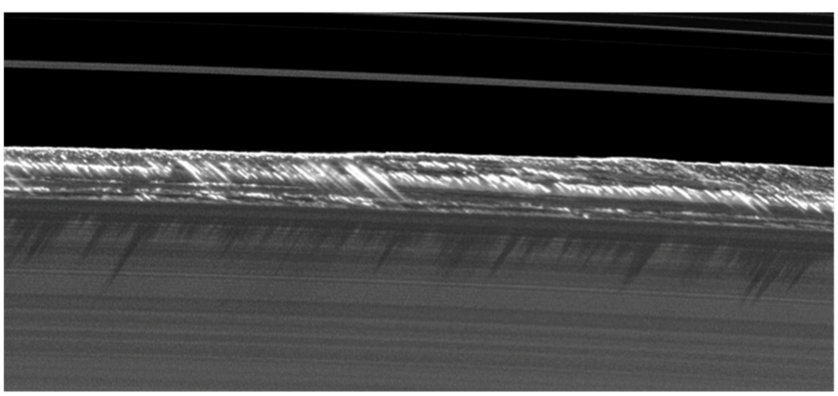

**Figure 3-13. Vertical structures at the edge of Saturn's B-ring. Among the tallest structures seen in Saturn's main rings, large objects rise abruptly from the edge of the B ring to cast long shadows on the ring. This image was taken by NASA's Cassini spacecraft two weeks before the planet's August 2009 equinox. (Credit: NASA/JPL/Space Science Institute)**

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## Saturn's Great Northern Storm of 2010–2011

Late in 2010, a giant storm quickly erupted in Saturn's relatively bland atmosphere (Figure 3-14). This type of storm typically occurs only once every 30 years, but this one arrived 10 years early, providing a unique observing opportunity for Cassini [Baines et al. 2018]. Within months, this storm completely encircled the planet with a swirling band of clouds and vortices [Sayanagi et al. 2013]. The largest temperature increases ever recorded for any planet were measured in the stratosphere and molecules never seen before in Saturn's upper atmosphere were detected. The storm began to fade away shortly after the vortex in its "head" collided with one in its "tail," about nine months after it began [Fletcher et al. 2011].

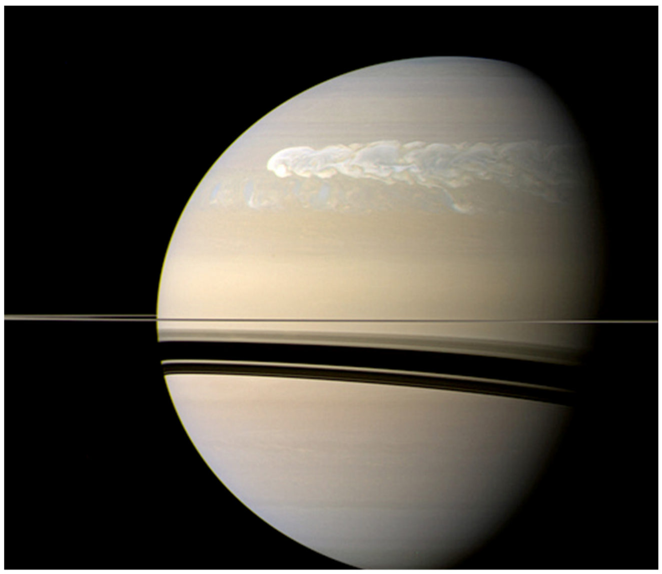

**Figure 3-14. Saturn's relatively tranquil atmosphere erupted with a storm of gigantic proportions in late 2010.**

## Saturn's North Polar Hexagon and Discovery of Giant Hurricanes at Both of Saturn's Poles

Saturn's polar regions surprised scientists with the presence of a long-lived hexagonal-shaped jet stream in the north and two hurricane-like storms at both poles. Their driving forces remain a mystery.

Saturn's alternating eastward and westward jet streams define the cloud bands that circle the planet on lines of constant latitude to within about one degree of each pole. One of the jet streams, near 75 degrees north latitude, forms a hexagonal pattern that is two Earth diameters across [Baines et al. 2009]. Voyager first discovered the hexagon, and it is still present at the same location after 35 years. Small clouds move eastward around the corners of the pattern. This hexagonal-shaped jet stream (Figure 3-15) is remarkable for its stability and longevity. Its source remains a mystery. Using Cassini CIRS thermal data of Saturn's North Pole, a new hexagonal structure,

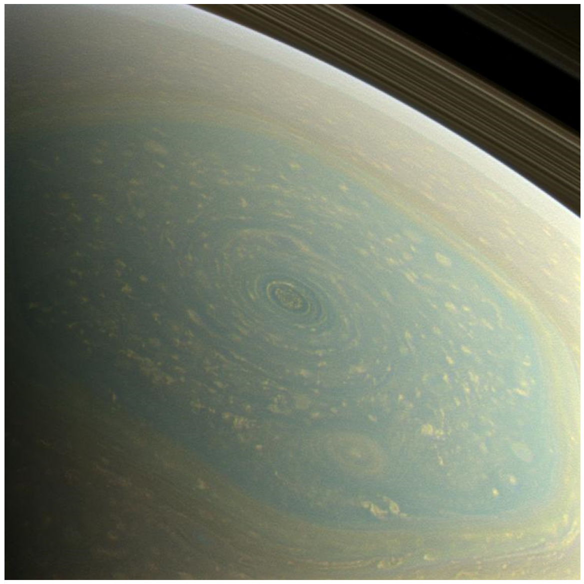

**Figure 3-15. The greenish hexagon, about two Earth diameters across, is clearly seen at Saturn's North Pole. (Credit: NASA/JPL/Space Science Institute).**

precisely matching the well-known hexagon, was recently discovered towering hundreds of kilometers above the cloud tops [Fletcher et al. 2018]. The presence of a newly detected hexagon in Saturn's northern summer stratosphere, which is connected to the familiar hexagon in some way, suggests that there is a great deal more to be learned about the dynamics at play in Saturn's atmosphere.

Cassini discovered hurricane-like storms at both of Saturn's pole. The hurricanes are about 50 times larger than a typical Earth hurricane and are centered exactly at the poles [Fletcher et al. 2008; Sayanagi et al. 2017]. In the south, Cassini discovered the clear eye of a hurricane-like vortex, with eyewall clouds towering 70 kilometers above the clouds in the center. There is a warm vortex at Saturn's North Pole as well. Each vortex shows well-developed eye walls [Dyudina et al. 2008].

## *Length of Saturn's day*

Saturn emits radio waves known as SKR that were first observed by Voyager in the early 1980s and were interpreted as an indicator of Saturn's internal rotation period. Cassini results showed that the SKR signals were not coming from the interior of Saturn as originally assumed. The SKR period changed from year to year, an impossibility if the SKR is tied to the interior. When Cassini first arrived at Saturn and measured the SKR period, data from the radio and plasma wave instrument also showed that the radio waves' frequencies were different in the northern and southern hemispheres [Gurnett et al. 2009]. In addition, planetary period oscillations observed in magnetic field data reveal a similar story: the period of these oscillations (although close to the expected planetary period of about 10.7 hours) changed over time, particularly with season, and were different in the northern and southern hemispheres [Provan, Cowley, and Nichols 2009]. Clearly the observations of SKR and its associated magnetic field are not coming from the interior.

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The origin of the multiple periodicities is not well understood but they are not related to Saturn's internal rotation rate. The magnetometer team searched for an offset between Saturn's rotation axis and magnetic field axis, to use the magnetic field variations from this offset to determine the length of Saturn's day. However, the offset was too small to determine Saturn's internal rotation rate [Dougherty et al. 2018].

Clues to the length of Saturn's day actually came from small waves detected in the rings. Saturn's ring system acts like a sensitive seismograph, providing a measure of Saturn's internal oscillations that allow a determination of its interior rotation rate. These vibrations, determined by Saturn's non-uniform internal structure, are probably driven by convection inside the planet, which cause oscillations in Saturn's gravity field that manifest themselves as waves in the rings. Modeling the propagation behavior of this collection of waves provides an interior rotation rate for Saturn of 10 hours 35.3 minutes ±2 minutes [Mankovich et al. 2019].

## Unexplored Territory: Probing the Gap between the Rings and Saturn

After 13 years in orbit, the Cassini-Huygens mission to Saturn ended with a truly unique set of science data. Cassini sent back its final bits of distinctive science data on September 15, 2017, as it plunged into Saturn's atmosphere, vaporizing to satisfy planetary protection requirements. Cassini's final phase covered roughly 10 months and ended after the first ever exploration of the region between the planet and its rings.

In late 2016, Cassini transitioned to a series of 20 Ring Grazing orbits with the closest approach (periapsis) just outside Saturn's F-ring, providing close flybys of tiny ring moons, and high-resolution views of Saturn's A- and F-rings. A final Titan flyby in late April 2017 propelled Cassini's periapsis across Saturn's main rings to initiate the Grand Finale orbits. Comprised of 22 orbits, Cassini repeatedly dove between Saturn's innermost rings and upper atmosphere to answer fundamental questions unaddressed earlier in the mission. The last orbit turned the spacecraft into the first Saturn atmospheric entry probe. Additional details about the science in these final orbits can be found in the discipline and team reports in Sections 3.1 and 3.2.

### *Close to Saturn: rings and ringmoons*

The Ring Grazing and Grand Finale orbits provided some of the highest-resolution remote sensing observations of the mission for studies of the five tiny ringmoons and Saturn's main rings. These orbits also provided a rare opportunity to fly through and directly sample the SKR region.

In the Ring Grazing orbits, Cassini performed the closest ever flybys of five of Saturn's tiny ringmoons, Pan, Daphnis, Atlas, Pandora, and Epimetheus. The surface characteristics of these moons are regulated by both accretion of a reddish material from Saturn's main rings and of icy grains originating in the Enceladus plume [Buratti et al. 2019]. The color and brightness of the moons inside or closest to the main rings (Pan, Daphnis, and Atlas) strongly resemble that of the rings. Figure 3-16 shows a central core surrounded by an equatorial ridge of ring particles for each of these three moons [Buratti et al. 2019]. For more details about these tiny ringmoons, see the Icy Satellites report in Section 3.1.

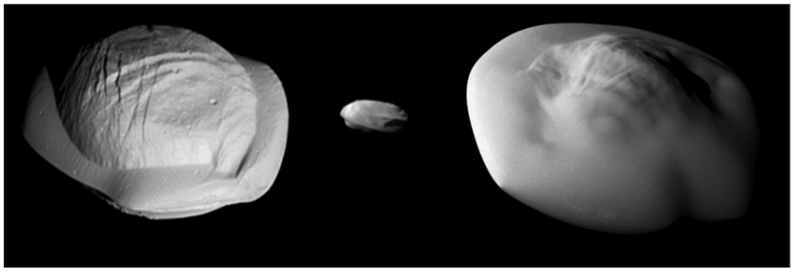

**Figure 3-16. Cassini images of Pan (left), Daphnis (center) and Atlas (right) as observed in 2017 during the closest flybys ever of these moons.**

The Cassini spacecraft passed very close to Saturn's main rings during its final year, and obtained very high-spatial-resolution images, spectral scans, and temperature scans [Tiscareno et al. 2019]. Embedded masses sculpt the main rings and new structures were discovered in the images, including new ring textures such as streaky C-ring plateaus and unexpected bands of particle clumping throughout the rings (Figure 3-17). Water ice band depths vary across the rings, and weaker ice bands were identified outside the Keeler gap in the A-ring. Many structures throughout the main rings and F-ring were studied in more detail—see Tiscareno and Murray [2018]. For more details about these ring observations, see the Ring report and team reports in Sections 3.1 and 3.2.

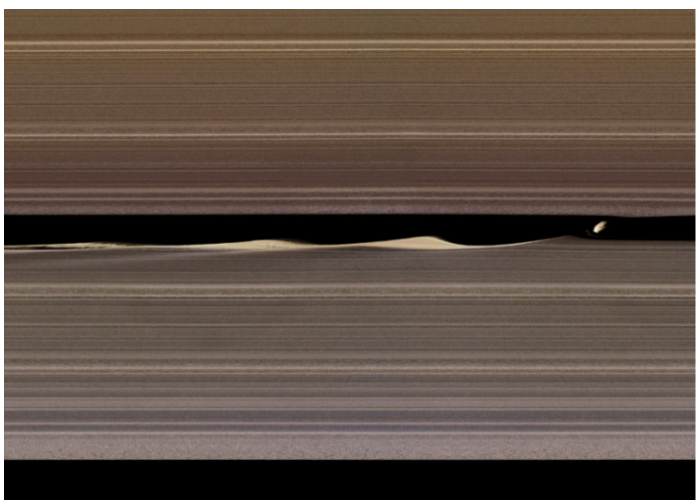

**Figure 3-17. Tiny Daphnis opens the Keeler gap and generates waves along one gap edge. The speckled texture is created by ring particles clumping together. This clumping is seen throughout the rings.**

The orbits during the final year provided an excellent opportunity to directly and repeatedly sample the top of the SKR emission region to determine its source [Lamy et al. 2018]. SKR is a sensitive diagnostic of Saturn's magnetospheric dynamics and auroral processes. In situ measurements are required to understand how these planetary radio emissions are generated. These emissions were found to be strongly time-variable from orbit to orbit, with a dependence on local time around Saturn. Only three SKR source regions were identified, all on the dawn side of Saturn, and controlled by the electron densities in the vicinity [Lamy et al. 2018]. These regions were embedded in upward currents associated with Saturn's auroral oval.

## *Diving through the gap*

During the Grand Finale orbits, numerous instruments performed in situ measurements while traversing the gap between the inner D-ring and the planet. MIMI, designed to measure energetic particles, measured an unexpected response to very small dust grains, about the size of large organic molecules [Mitchell et al. 2018]. Ring dust in the submicron range was detected by CDA, and ring composition was directly measured for the first time [Hsu et al. 2018]. The composition of the volatiles in the gap was revealed by INMS, indicating an array of gases and organic compounds [Waite et al. 2018]. The MIMI instrument also identified an inner radiation belt in this gap region [Roussos et al. 2018].

MIMI detected tiny nanograin ring particles, within ±2° of the equator, entering Saturn's equatorial atmosphere directly from the inner D-ring, possibly from the bright D68 ringlet [Mitchell et al. 2018]. Collisions with hydrogen atoms provide enough drag to decelerate the particles, until they plunge into Saturn's atmosphere. This continuous rain of particles produces a lower limit of ~5 kg $s^{-1}$ into the atmosphere. Particles at higher latitudes are charged and transported along the magnetic field lines as "ring rain" [Hsu et al. 2018; Mitchell et al. 2018].

CDA directly measured the mass and composition of particles originating in Saturn's main rings to characterize the material falling into Saturn's atmosphere. CDA primarily detected tiny nanograins with the highest peak flux near Saturn's equator and two secondary peaks at mid-latitudes, one on each side of the rings [Hsu et al. 2018], consistent with previously detected "ring rain" [O'Donoghue et al. 2013]. Two separate nanograin compositions were identified, water ice grains and silicate grains [Hsu et al. 2018]. Silicate grains comprised about one-third of the identified nanograins, much greater than the estimated bulk silicate composition of typically only a few percent [Cuzzi et al. 2010].

The INMS instrument directly observed the interaction between the rings and Saturn's atmosphere, measuring the in situ atmospheric and ionospheric composition of Saturn's equatorial atmosphere for the first time. Ring volatiles from the D-ring were detected, including water, methane, ammonia, carbon monoxide and/or molecular nitrogen, and carbon dioxide enter Saturn's atmosphere along the ring plane. INMS also measured an influx of organic-rich nanoparticles from the rings that further modifies the composition and structure of the equatorial atmosphere (Figure 3-18). The estimated mass influx rate was 5,000 to 40,000 kg $s^{-1}$, considerably higher than the MIMI estimates [Mitchell et al. 2018; Waite et al. 2018].

During the final orbits, an inner radiation belt was detected by MIMI in the gap between the D-ring and top of Saturn's atmosphere [Roussos et al. 2018]. Saturn's main rings inhibit the inward passage of trapped charged particles that form radiation belts. Hence, the radiation belts outside the main rings cannot interact with the inner radiation belt, providing an opportunity to study the inner belt and its interactions with the D-ring. One possible source for the inner radiation belt is the Cosmic Ray Albedo Neutron Decay (CRAND). Ringlets in the D-ring, including D68 and D73, control the structure and outer boundary, respectively, of this radiation belt [Roussos et al. 2018].

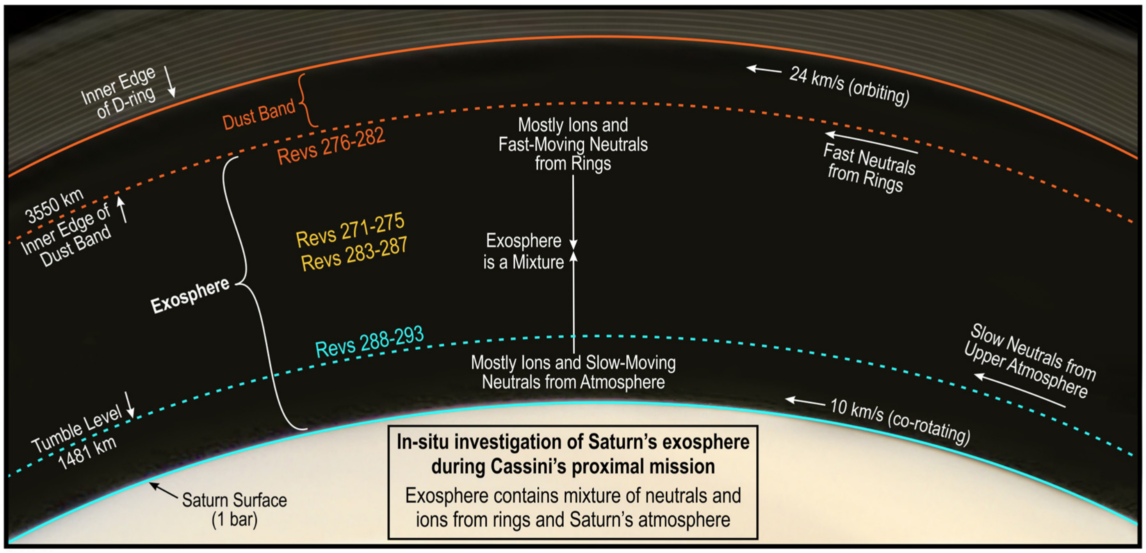


**Figure 3-18. Geometry of Cassini's Grand Finale orbits. Left panel: A schematic drawing showing the altitude coverage of the orbits (revs) during the Grand Finale phase of the Cassini mission from a polar perspective. The region is bounded above by the D-ring and below by the 1 bar pressure level of Saturn's atmosphere. From Waite et al. [2018].**

## Window inside Saturn: Internal Structure from Gravity and Magnetic Fields

Cassini's Grand Finale orbits enabled the highest resolution gravity and magnetic field measurements of Saturn for the entire mission. The behavior of Saturn's internal gravity and magnetic fields provides a window into the interior of the planet.

Six of the Grand Finale orbits were designed for gravity measurements. During these orbits unique gravity signatures were recorded to determine the mass distribution in Saturn's interior and the mass of Saturn's main rings [Iess et al. 2019]. The measured values of Saturn's gravitational harmonics require deep differential rotation to a depth of about ~9,000 km inside the planet (down to about 0.7 Saturn radii). This depth may correspond to the levels of magnetic dissipation. Saturn's rocky core is about 15–18 Earth masses. The ring mass is 0.41 Mimas masses, pointing to a relatively young ring age, perhaps only $10^7$–$10^8$ years old [Iess et al. 2019].

All 22 orbits provided the highest resolution magnetic field measurements of Saturn's internal and external fields since Cassini's passage above

> Cassini's final year was like a brand-new mission as it explored a region of the Saturn system unexplored by any previous outer planet spacecraft.

the rings during SOI. One of the Grand Finale surprises was the exceptionally small observed tilt (less than 0.0095°) between Saturn's spin-axis and its magnetic axis [Dougherty et al. 2018]. Saturn's magnetic field is considerably more axisymmetric than any other planetary magnetic field in our solar system, making it challenging to explain with current theories. MAG data provide interesting insights into Saturn's conducting magnetic region. For instance, zonal flows imply differential rotation, which is consistent with Cassini's gravity measurements [Iess et al. 2019], while the higher order magnetic moments hint that secondary dynamo action may be at work in the semi-conducting region of Saturn [Dougherty et al. 2018].

The magnetometer team also discovered a strong, low latitude field-aligned current (FAC) system, situated between the inner edge of the D-ring and the top of Saturn's atmosphere [Dougherty et al. 2018]. This current is comparable in strength to the currents observed in the auroral zone and as such, may be part of a global current system.

Cassini's final year was like a brand-new mission as it explored a region of the Saturn system unexplored by any previous outer planet spacecraft. These new data required new theories and new ideas. Cassini's final Earth-bound transmission occurred on September 15, 2017, as it plunged into the planet, sending its last bits about the directly sampled atmosphere to Earth, then vaporizing in Saturn's atmosphere. This protective measure ensured that any hardy, Earthly microbes that might have survived onboard Cassini did not inadvertently contaminate either Enceladus or Titan.

Only a few of the many Cassini scientific highlights were discussed here. In the coming years many more Cassini discoveries remain to be found in this incredibly rich data set.

A list of some of Cassini's key discoveries and findings is given in Table 3-10 to illustrate the breadth and depth of this incredible mission. Cassini's rich set of science instruments led to many new discoveries across all five science disciplines. Many more discoveries and findings are discussed in the discipline and team reports in Sections 3.1 and 3.2.

**Table 3-10. Cassini discoveries: A partial list of Cassini's key findings and discoveries.**

| |
|---|
| **Huygens landing on Titan.** Huygens probe lands on the surface of Titan and makes critical atmospheric and surface measurements. |
| **Geologic activity at Enceladus.** Active plume discovered at south pole; Enceladus' plume creates Saturn's E-ring and alters other moons' surfaces; spectacular south polar terrain tectonics; enormous measurable endogenic heat. |
| **Lakes and seas on Titan.** Discovery of Titan's polar lakes/seas; specular reflection of sunlight confirms liquid in Kraken Mare. |
| **Saturn giant storm.** Saturn daytime lightning seen for the first time. Unprecedented, long-lasting 80K stratospheric temperature increase and new molecules observed in aftermath. Thunderstorms uplift carbon, water ice, and ammonia ice from depth. |
| **Saturn kilometric radiation.** North-south periods are different and change unpredictably. |
| **Vertical structure in Saturn's rings.** The 10 m thick rings, edge-on, show huge vertical structures created by gravitational interaction with moons; rippled rings show evidence for large impacts over the centuries. |
| **Enceladus' variable plume emission.** Gravitational tides cause fissures to periodically open and close depending on orbital distance from Saturn. |
| **Subsurface ocean on Titan.** Gravity and radar measurements indicate the presence of a subsurface ocean and soft interior. |
| **Two new populations of objects in the rings.** Propellers and self-gravity wakes reveal dynamic structure of the rings. |

**Table 3-10. Cassini discoveries: A partial list of Cassini's key findings and discoveries.**

| |
|---|
| **Depth of a Titan sea.** Radar sees secondary echo while sounding Ligea Mare, detecting sea bottom. Depth of other seas and small lakes detected also. |
| **Enceladus global ocean.** Global ocean discovered beneath Enceladus' icy crust from radio science measurements and detection of excess libration. |
| **Ring impact clouds.** The rings make good detectors of meteorite impacts, based on generated debris clouds. |
| **Massive hurricanes at Saturn's north and south pole.** Hurricanes discovered at north and south poles. |
| **Phoebe flyby.** First encounter with an object in the Saturn system that likely originated in the Kuiper Belt. |
| **Formation of a polar vortex over Titan's south pole**. Seasonal changes caught in the act on Titan. |
| **Enceladus plume composition.** Jets are shown to contain salty particles, organic molecules, and ammonia ice. |
| **Enceladus hydrothermal vents.** Evidence for hydrothermal vents, including detection of nanosilica grains and excess hydrogen in the plume. |
| **Most of Titan's seas and lakes are at its north pole.** Discovery of lakes in Titan's polar regions, but with vast majority at the north pole. |
| **Saturn polar hexagon rediscovered.** Discovered by Voyager, Cassini found this jet stream long lived. |
| **Thermal anomalies at Mimas and Tethys.** Electron bombardment of parts of their surfaces brings about modification of surface thermal properties. |
| **Weather on Titan.** Methane rains (part of Titan's methane "hydrological" cycle) cause visible changes on Titan's surface. |
| **Saturn's magnetosphere plentiful with water.** $H_2O$ products dominate the magnetospheric chemical species; expected nitrogen not found. |
| **Iapetus' albedo dichotomy and equatorial ridge.** Phoebe dust darkens Iapetus surface. Thermal migration of volatiles causes color dichotomy. Equatorial ridge observed, perhaps a relic of ancient ring of impactors. |
| **Menagerie of Moon Surfaces.** Satellites exhibit a striking diversity of surface properties, e.g., Hyperion, Iapetus, and tiny ringmoons. |
| **Saturn rotation mystery.** Variable SKR rates and apparent lack of magnetic axis tilt leaves internal rotation rate a mystery. |
| **Rings capture Saturn's internal dynamics.** Unique spiral waves in rings provide windows into Saturn's atmospheric oscillations and interior. May provide a rotation rate for the interior of Saturn. |
| **Organic 'building blocks' discovered in Titan's atmosphere.** The presence of heavy negative ions in Titan's ionosphere appeared to act as organic building blocks in recombination with large positive ions to create more complex molecules as precursors of aerosol and haze particles. |
| **Supernovae shockwaves.** Unusually strong solar wind interacted with magnetosphere to accelerate particles to relativistic speeds, a model for stellar-explosion shockwaves. |
| **Nanograins in gap between innermost ring and top of Saturn's atmosphere.** Predominant particle population in the gap is tiny nanograins. Complex organic compounds embedded in water nanograins rain down from Saturn's rings into its upper atmosphere. Composition includes water and silicates, and also methane, ammonia, carbon monoxide, nitrogen and carbon dioxide. Some inner-ring particles and gases fall directly into Saturn's atmosphere. |
| **Ring rain.** Some ring particles take on electric charges and spiral along magnetic field lines, falling into Saturn at higher latitudes as "ring rain." |
| **New inner radiation belt.** New radiation belt discovered very close to the planet and is made up of very energetic particles. |
| **Tilt of magnetic field axis.** Saturn's magnetic field axis is almost completely aligned with its spin axis and is very close to zero. |
| **Electric current connects to top of Saturn's atmosphere.** A previously unknown electric current system that connects rings to top of Saturn's atmosphere. |
| **Asymmetric ring structure.** Ring particle clumping appear to be ubiquitous across the main rings, including within C-ring plateaus. |
| **Mass of rings points to young ring age.** The measured mass of the rings, less than 0.5 Mimas masses, points to a ring age much younger than the age of the solar system. |
| **Saturn differential rotation.** Gravity measurements indicate differential rotation inside Saturn and wind depths of about 9.000 km. |

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## Major Open Questions Resulting from Cassini

While making amazing discoveries within the Saturn system and changing the paradigm of where to search for life in the solar system, the Cassini mission left a number of open questions for future study. Some of the answers are buried in the wealth of data that will be analyzed by current and future generations of scientists. Some await future exploration of the Saturn system. Below is a summary of some of these questions, organized by science discipline. For more details and other open questions, please see the Sections 3.1 and 3.2 discipline and team reports, all of which have submitted open questions relevant to their own discipline or team.

### *Icy Satellites*

- What are some of the minor constituents of the Saturnian moons, and are they endogenic or exogenic? If exogenic, is the accretional process still ongoing?
- What is the total heat production on Enceladus and how and why does it vary? What does this imply about the cause of activity on the moon? What is the source of the organic material in the plume of Enceladus?
- Is there residual activity on Dione and Tethys, and if so, what does this imply about their recent history? Are the red streaks on Tethys evidence for such activity?
- What caused the ridge on Iapetus? Is it evidence for a past ring? Did other moons have rings in the past?
- Why does the origin of the moons of Jupiter and Saturn seem to diverge, with the Jovian moons being formed relative to their position from Jupiter, and the Saturnian moons being formed by stochastic events?
- To what extent do magnetospheric particles alter the optical properties of the moons? Does contamination by ring particles, including those from the E-ring dominate this process?

### *Titan*

- What are the abundances of the heavy noble gases in Titan's atmosphere and surface?
- How do you go from the very heavy ions and molecular species to haze particles?
- What are the origin, evolution, and ultimate fate of Titan's atmosphere?
- How did the lakes and sea basins form?
- What is the nature and extent of the exchange between the surface/atmosphere and deep subsurface and ocean?
- Is there active cryovolcanism on Titan?

## *Saturn*

- What is Saturn's global water abundance and what is its role in bringing heat to the surface? What is the role of moist convection in maintaining the large-scale motions?
- What is Saturn's rotation period, and what is the spread of periods if differential rotation persists into the interior? Has kronoseismology, as exhibited by the Saturn-driven waves in the main rings, finally yielded an answer to this question?
- How will additional insights from the combination of ring seismometry, gravity sounding, and magnetic field sounding improve the understanding of Saturn's internal equation of state, mass distribution, composition, and temperature distribution?
- What is Saturn's noble gas abundances including helium, as done for Jupiter by the Galileo probe? Does helium rain play a role in reducing the He/H in Saturn's molecular envelope?
- Using the power of ring seismometry and gravity sounding, improve the understanding of Saturn's internal equation of state, mass distribution, composition, and temperature distribution.
- What sustains Saturn's north polar hurricane and hexagonal jet stream?

## *Rings*

- What is the radial profile of ring mass?
- What is causing the myriad of unexplained ring structures? For instance, what is creating and sustaining the entire ensemble of so-called "plateaus" in the outer C-ring?
- What is creating the unusually "red" color of the A and B rings, which are more than 95% water ice? Is it due to organic material, based on a combination of remote and in-situ measurements? How does the composition vary from place to place and on a range of scales?
- What is the age of the rings? Current data indicate that the rings seem to be much younger than the age of the solar system.
- How much about Saturn's internal structure and dynamics can be inferred from ring features?

## *MAPS*

- What is the cause of the rotational modulation in axisymmetric magnetosphere configuration?

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- How are mass and magnetic flux transported in the middle and outer magnetosphere?
- Need for more plasma measurements in auroral acceleration and source region of related SKR. Will the previously observed hemispheric dichotomy in the Saturn kilometric radiation period reappear?
- Need for better time resolution and coverage to understand the Enceladus' plume-magnetosphere interaction.
- What is the composition of the negative ions at Titan and >100 amu positive ions?
- What is the source of energy for the hot coronas/upper atmospheres of all four giant planets?

The Cassini mission has successfully answered many scientific questions and posed many new ones. A robust combination of future missions to the Saturn system, along with continued research and analysis, may yield answers to some of the questions listed above questions and generate new ones. The next Planetary Science Decadal Survey will pose its own questions based on Cassini results. One thing is clear: the questions left unanswered by Cassini and Huygens cry out for return missions to the Saturn system.

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The Cassini-Huygens mission is a joint undertaking by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Agenzia Spaziale Italiana (ASI) is also a major partner via a bilateral agreement with NASA. Cassini is managed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract from NASA.

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# Acronyms

*Note: For a complete list of Acronyms, refer to Cassini Acronyms – Attachment A.*

| | |
|---|---|
| ACP | Aerosol Collector Pyrolyser |
| AO | Announcements of Opportunity |
| ASI | Agenzia Spaziale Italiana |
| CAPS | Cassini Plasma Spectrometer |
| CDA | Cosmic Dust Analyzer |
| CEM | Cassini Equinox Mission |
| CIRS | Composite Infrared Spectrometer |
| Co-I | Co-Investigator |
| CRAND | Cosmic Ray Albedo Neutron Decay |
| CSM | Cassini Solstice Mission |
| DISR | Descent Imager and Spectral Radiometer |
| DSN | Deep Space Network |
| DWE | Doppler Wind Experiment |
| DWG | Discipline Working Group |
| ESA | European Space Agency |
| ESOC | European Operations Center |
| FAC | Field-Aligned Current |
| GCMS | Gas Chromatograph and Mass Spectrometer |
| GF | Grand Finale |
| GWE | Gravitational Wave Experiment |
| HASI | Huygens Atmospheric Structure Instrument |
| HGA | High-Gain Antenna |
| HPOC | Huygens Operations Center |
| HSWT | Huygens Science Working Team |
| ICO | Instrument Checkout |
| IDS | Interdisciplinary Scientist |
| IDS | Interdisciplinary Scientist |
| INMS | Ion and Neutral Mass Spectrometer |
| IS | Investigation Scientist |
| ISS | Imaging Science Subsystem |
| JPL | Jet Propulsion Laboratory |
| MAG | Magnetometer |
| MIMI | Magnetospheric Imaging Instrument |
| NSM | Northern Summer Mission |
| ORS | Optical Remote Sensing |
| OST | Operations Science Team |
| PI | Principal Investigator |

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| | |
|---|---|
| PM | Prime Mission |
| PSG | Project Science Group |
| PVO | Pioneer Venus Orbiter |
| RADAR | Titan Radar Mapper |
| RG | Ring Grazing (F-ring orbits) |
| RotR | Rules of the Road |
| RPWS | Radio and Plasma Wave Science |
| RSS | Radio Science Subsystem |
| SAMWG | Saturn Atmospheric Working Group |
| SED | Saturn Electrostatic Discharge |
| SKR | Saturn Kilometric Radiation |
| SOI | Saturn Orbit Insertion |
| SSP | Surface Science Package |
| TAMWG | Titan Atmospheric Working Group |
| TL | Team Leader |
| TM | Team Member |
| TWT | Target Working Team |
| UT | Universal Time |
| UVIS | Ultraviolet Imaging Spectrograph |
| VIMS | Visible and Infrared Mapping Spectrometer |

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***Disclaimer:*** *The partial list of references below correspond with in-text references indicated in this report. For all other Cassini references, refer to Attachment B – References & Bibliographies; Attachment C – Cassini Science Bibliographies; the sections entitled References contributed by individual Cassini instrument and discipline teams located in Volume 1 Sections 3.1 and 3.2 Science Results; and other resources outside of the Cassini Final Mission Report.*

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Jet Propulsion Laboratory
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# MAPS Rules of the Road

volume 1 Mission Overview,
Science Objectives and Results

CASSINI FINAL MISSION REPORT 2019

# Appendix A

## What Are the MAPS Rules of the Road

The original AO for Cassini in 1989 included the following list of goals for the study of the magnetosphere of Saturn.

- Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of the Saturn kilometric radiation.
- Determine current systems, composition, sources and sinks of magnetospheric charged particles.
- Investigate wave-particle interactions and dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interaction with the solar wind, satellites and the rings.
- Study the effect of Titan's interaction with the solar wind and the magnetospheric plasma.
- Investigate the interaction of Titan's atmosphere and exosphere with the surrounding plasma.

These goals are very general and broad reaching and it is clear that they could not be achieved by any single instrument and certainly not without the sharing of data between instrument teams. MAPS, led by its two IDSs, started early to make plans to address this.

One of the important actions by the MAPS IDS team was to propose and manage the creation of the "MAPS Rules of the Road" (hereafter RotR). The overarching goal of the RotR document was to create an environment where collaboration between teams was the norm. Such an environment would require the MAPS PIs and their teams to feel comfortable sharing their data with other teams and to have the assurance that their data would be handled fairly. The MAPS RotR contains an itemized description of what data can and should be shared between the MAPS instrument teams, how that data is allowed to be used, and who is responsible for overseeing the proper use of shared data. Although the MAPS RotR are by no means perfect, they provided a foundation on which the scientific success of the Cassini MAPS team could be built.

## Development of the MAPS Rules of the Road

### *Motivation: MAPS science naturally requires collaboration*

The scientific questions studied by the MAPS working group are based heavily on fundamental plasma physics including neutral and charged particles, particle sources and losses, particle energization and transport, the influence of electric and magnetic fields and coupling with Saturn and its moons. The processes are fundamentally governed by Maxwell's equations, which couple particle related quantities (current, charge) with electric and magnetic fields. Furthermore, Saturn's moons (Titan in particular) are places where chemical processes are highly important. The dependence of MAPS science on fundamental principles naturally results in the need for data from multiple instruments because of:

- Interactions of neutral particles, ions and electrons
- Lower energy particles make up the bulk of the plasma density while higher energy particles contribute significantly to the plasma pressure
- Saturn's magnetic field, coupled with fast planetary rotation, drives particle motion and plasma transport
- Identification of neutral and ion species leads to understanding of sources as well as the fundamental chemical processes involved

Because of the inter-instrumental nature of the MAPS Cassini science questions, it was clear that the MAPS instrument teams could not achieve all of their own, individual science goals or the mission science goals without data sharing. Fortunately, because of the fundamental, physics-based need for data sharing in magnetosphere physics, the magnetospheric and plasma science community has a historical track record of sharing data. Although this community has a long history of sharing mission data, it was recognized that formalizing a data sharing plan would further foster the collaborative environment in the MAPS community and would likely greatly enhance the return from the Cassini Mission. I concluded that a data sharing plan needed to be a topic that was addressed and worked out early in the mission.

## *Venus Express as a Model*

The MAPS RotR were modeled after the Pioneer Venus Orbiter (PVO) rules of the road. Unfortunately, it was not possible to find the original PVO RotR documents to include here and it was also not possible to determine who wrote the original RotR for the PVO. I was a member of the PVO science team and was familiar with the PVO RotR. I concluded that the Cassini MAPS teams could benefit from a formal data sharing agreement that outlined specific regulations for how data would be shared amongst the instruments team. I presented the PVO RotR document to the MAPS PIs around 1995 and to the entire Cassini PSG meeting soon after launch.

## *The Design and Implementation Process*

IDS Gombosi presented the idea that MAPS needed a data sharing plan and suggested to the PIs that the PVO RotR was a document that provided a good place to start a discussion. The presentation of the PVO RotR document by IDS Gombosi to the MAPS PIs was generally received positively and a discussion of what the MAPS RotR should look like began. It is important to note that the MAPS RotR is a data sharing plan that was mutually developed and agreed on by each of the MAPS instrument PIs. The document was not created from above and forced on the PIs. It was created together with the PIs through discussion and negotiation. This process allowed each PI to be satisfied that their individual needs would be addressed and created an atmosphere of buy in by all instrument teams.

The MAPS RotR document retained all the initial points of the PVO RotR document. However, the MAPS PIs suggested a few modifications, one of which was very significant. In point 1, the MAPS IDS's added the phrase "It is the responsibility of MAPS PIs to ensure that the Rules-of-the-Road are observed by their team." Although the quantity of added text was minimal, the intent of the text became very important during the mission. The PIs felt that it was important to directly indicate who was responsible for ensuring that the RotR where followed. Asking each PI to be responsible for their own team's use of data from other instruments had several important consequences. First, for a PI to fulfill this responsibility it required them to know what research was being conducted by their teams. The PIs did not micromanage the research, but by being aware of what their team members were doing they could enforce the RotR and foster more collaborations. Second, by assigning responsibility for oversight it was relatively straight forward to handle the occasional violation of the RotR.

It is important to note that final text for the document was accepted in the year 2000, four years before the arrival of Cassini at Saturn and before the flyby of Jupiter. The agreement was in place well before any of the truly important scientific data was beginning to be collected. In fact, having the RotR in place during the cruise phase allowed teams to begin to understand how to operate within the rules and to start sharing data with trust and confidence early on. By the time Cassini arrived at Saturn, teams shared data reasonably well because they already had experience.

Beyond indicating that the responsibility for oversight of the use of shared data belonged to the PIs, the MAPS RotR contained several key stipulations. Perhaps equally important to the data sharing oversight, the document makes it very clear that instrument teams are expected to share their data (item 4). Although such data sharing is typical in the magnetosphere and plasma community, the formalized, agreed upon statement put MAPS on a stable foundation for collaborations during the mission. The RotR also outlines several limitations to what data would be shared and how that data could be used. First, the document makes clear that instrument PIs and their Co-Is are responsible for the initial analysis, interpretation, and publication of these data. This statement was very important because it clarified that PIs and instrument teams would have first right to publish unique data or discoveries made by their instrument before having to share data with the MAPS team. The RotR also makes it clear that data is shared for the purpose of conducting correlative and collaborative studies and should not be used for studies that could be done by the instrument team alone. Finally, when data shared by another instrument is being used for a correlative study, the RotR indicate that the instrument PI and the team should be informed of how the data will be used. In addition, the RotR indicates that researchers using other instruments data

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should invite members of the appropriate instrument team, through the PI, to participate in the study and that this invitation should be made very early in the research process.

Because data was expected to be shared broadly between the MAPS instrument teams it was important that the RotR indicate with whom data could be shared. MAPS data was to be shared within the MAPS instruments teams, under the direction of the instrument PIs. The data and summary plots created on MAPSview were not to be shared beyond the MAPS team members without approval of the PIs of the relevant instrument.

Finally, two important stipulations of the MAPS RotR related to roles of the IDSs within the MAPS group: proper role of an IDS and summary plots and a key parameter database. Both of these items are addressed in more detail in the MAPS Data Sharing document. Here we note that as the RotR document was being created the MAPS IDSs expressed their strong belief that their job was not to complete with the instrument teams but rather to facilitate individual teams, facilitate collaboration between teams, and to bring skills or models to the table that none of the instrument teams had access to. The MAPS RotR formalized this role. In the context of facilitating collaboration, the MAPS IDSs felt it was important create a key parameter database and summary plots including all MAPS instrument data. These resources where to be used for quickly finding correlations or to quickly evaluate observed events. The RotR document indicates that this key parameter data and the quick look plots are to be treated the same as full quality instrument data products.

## *Rules of the Road during the Mission*

### Successes

The most important success of the MAPS RotR is the incredible science return that has come from the MAPS working group. A quick review of papers produced by MAPS investigators shows that a majority of papers have co-authors from more than one instrument. Although it is not possible to determine the quantitative impact the RotR had on the number of collaborative papers published by MAPS, our feeling is that the RotR greatly enhanced the ease of sharing data and teams willingness to share and therefore greatly increased the number of papers produced by MAPS.

During the mission, there was only one serious breach of the MAPS RotR. Given the considerable amount of data shared and the breadth and quality of the collaborations this is clearly a success.

Finally, as mentioned above, the process for creating the MAPS RotR was not top down. It was suggested by the MAPS IDS but it was not forced on the PIs. The process of modifying the PVO RotR to meet the needs of the Cassini mission and of implementing the RotR was in the hands of the PIs. This process assured that each PI could be satisfied that the needs of their individual team would be addressed and that the MAPS RotR would be consistent with individual team’s internal policies.

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The active support of the PIs for the development and implementation resulted in an atmosphere where sharing of data was the norm and where teams trusted that their data and their interests would be protected.

## Challenges

Because the MAPS RotR were agreed upon by each of the MAPS PIs early in the mission, there were no problems with teams complaining about sharing data or teams restricting access to data that was important for collaborative studies. However, with a group as large as the Cassini MAPS team, and with the generally open sharing of data from all the MAPS instruments, it was likely that at some point data would be treated out of accordance with the RotR.

Although the RotR worked remarkably well in helping MAPS teams to share data openly and conduct many collaborative studies, there were a few occasions when the RotR were not followed. In almost every case, the breach was inadvertent, not malicious and did not result from a blatant lack of ethics. Nevertheless, some of the breaches where quite problematic and caused justified concern for the PIs involved. Very minor breaches where typically handled between the PIs whose teams were involved. However, in one or two cases, the RotR had to be reiterated at a MAPS working group meeting at a PSG and the MAPS IDSs were called on to reaffirm the data sharing agreement. At the same time, PIs were reminded to talk with their teams about the issue and to take a firmer role in overseeing how data from other instruments was being used. In each case, the value of the RotR was amplified because it provided a foundation for the discussion and resolution. The RotR could be consulted to clearly delineate how the offending action violated the RotR and what the appropriate course of action should have been.

## Cassini Mission Rules of the Road

The MAPS RotR document was clearly a success in fostering data sharing between the MAP teams. This success led the Cassini Mission Project Scientist to consult with the MAPS IDS in implementing a RotR document for the broader mission. The creation of that document was discussed during the 1998–2002 period and the final Cassini RotR was accepted by the Executive PSG in 2002.

## Lessons Learned

As outlined above, the most important aspect of the RotR was that it clarified the rights of teams with respect to using their own data, their responsibility to share their data and proper use of other team's data. In addition, it clearly laid out who was responsible for assuring the team members followed the RotR. These key parts of the RotR greatly reduced the data "ownership" conflicts that often prevent the open sharing of data between instrument teams.

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Moving from “the data is ours” point of view to the open sharing of data requires a culture change. Although the MAPS community has a track record of sharing data (for the reasons outlined above), the RotR document gave PIs and their teams confidence that their data would be protected and used correctly. This allowed teams to begin to share data and then to observe the mutual benefit that comes from sharing. This is perhaps one of the most important keys to a culture change. Teams have to see that sharing is mutually beneficial to feel truly comfortable openly sharing their data. The MAPS RotR document, or something like it, can have the effect of opening the door enough for teams to gain confidence and move toward the culture change needed for open sharing of data.

Finally, we note that the collaborative, data sharing culture is easier to achieve for in-situ instruments, as opposed to remote sensing instruments, due to the nature of the science addressed. As outlined above, data from multiple in-situ instruments is typically required in order to fully understand a phenomenon or an event. On the other hand, the nature of the science done by remote sensing teams is such that a single instrument can often make major advanced without the need for data from other teams. The nature of images also makes them more prone to someone outside a team being able to make discovery where for in-situ instrument this is much more unlikely. For this reason, it is clear that achieving a collaborative data sharing culture is easier for in-situ (MAPS) instrument teams than it is for remote sensing teams.

## Cassini/Huygens Mission MAPS Discipline Working Group Rules of the Road (September 2000)

The MAPS DWG of the Cassini Huygens Mission agrees to the following set of procedures and rules to assure an orderly and efficient analysis and interpretation of the mission's scientific results.

1. Instrument Principal Investigators (PI), Science Team Leaders (TL) and Interdisciplinary Scientists (IDS) will be designated MAPS PIs. It is the responsibility of MAPS PIs to ensure that the Rules-of-the-Road are observed by their team. MAPS instrument PIs and TLs will be referred to as instrument PIs. The MAPS team is composed of all MAPS PIs, their Co-Is, team members and associates (such as students, postdocs, etc.). Each team member must be sponsored by a MAPS PI.

### *Gombosi: MAPS Rules-of-the Road 6*

1. Each instrument PI is responsible for the analysis of data from his/her instrument. The instrument PIs and their Co-Is are responsible for the initial analysis, interpretation, and publication of these data.

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2. IDSs are expected, under normal circumstances, to carry out investigations that involve more than one instrument. This may occur either as a result of their proposing such investigation, or their being invited to participate in investigations by other MAPS PIs. When investigations are proposed in an area in which an IDS is known to have an interest, the normal procedure will be to invite him/her to participate.

3. All instrument PIs are expected to contribute their processed data for MAPS team use. However, these data are to be used for correlative studies only.

4. When data from an instrument are used in a correlative study, the instrument PI responsible for the data must be informed of their use, and invited at an early time (preferably before the investigation begins) to participate (directly or through designated associates) in the study. The collaborators from the data providing instrument should be invited, through the PI, to be co-authors of any resulting publication or presentation (including abstract of a presentation).

5. The combined summary plots are made available to MAPS to identify possible scientifically interesting events. These plots are not intended for publication purposes, and may not be published without the specific authorization of the appropriate instrument PI. However, summary plots can be used in oral presentations to demonstrate potential new science. In such cases appropriate credit must be given to the instrument PI.

6. Each MAPS member entrusted with the summary plots are required to see that they are not distributed beyond the MAPS community without the specific permission of the instrument PIs who contributed data to the summary plot.

7. Any instrument PI can release data from his/her instrument to anyone, but no data can be released or published without the permission of the appropriate instrument PI.

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