# THE CASSINI/HUYGENS MISSION TO THE SATURNIAN SYSTEM

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**Abstract.** The international *Cassini/Huygens* mission consists of the *Cassini Saturn Orbiter* spacecraft and the *Huygens Titan Probe* that is targeted for entry into the atmosphere of Saturn's largest moon, Titan. From launch on October 15, 1997 to arrival at Saturn in July 2004, *Cassini/Huygens* will travel over three billion kilometers. Once in orbit about Saturn, *Huygen*s is released from the *orbiter* and enters Titan's atmosphere. The *Probe* descends by parachute and measures the properties of the atmosphere. If the landing is gentle, the properties of the surface will be measured too. Then the *orbiter* commences a four-year tour of the Saturnian system with 45 flybys of Titan and multiple encounters with the icy moons. The rings, the magnetosphere and Saturn itself are all studied as well as the interactions among them.

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## 1. Introduction

Saturn is visible to the naked eye and virtually every ancient civilization noted its apparitions. Saturn is the second most massive planet in the solar system and it has the most extensive system of rings. It has a planet-sized satellite, Titan, that has a dense, veiling atmosphere. It has at least twenty-nine additional icy satellites[1]. Each offers a world to explore. The Saturnian magnetosphere is immense. It maintains dynamical interfaces with the solar wind and with the atmosphere of Titan. The *Cassini/Huygens* mission makes both *in situ* measurements, and remote sensing observations of targets under favorable geometric and temporal conditions that are not available from Earth (e.g., range and angles of illumination and emission; events such as occultations and eclipses).

Progress in understanding the planets as bodies orbiting the Sun advanced with the invention of instruments to accurately measure celestial positions, and the subsequent cataloging of these precise observations. Developments in mathematics and the discovery of the theory of gravitational attraction provided a great leap forward. The pace of progress quickened with the invention of the telescope and its application to the sky by Galileo. Table I provides a brief chronology of the major events in the exploration of the Saturnian system. The advent of spacecraft exploration has again quickened the pace of discovery anew. It is expected that the availability of orbital observations and the atmospheric probing of Titan's atmosphere by the *Cassini/Huygens* mission, will accelerate that pace of progress in gaining new knowledge.

### 1.1. Naming the Mission and the Spacecraft

The overall mission and the *Orbiter* spacecraft (or mother ship) is named after the French/Italian astronomer Giovanni Domenico Cassini, who discovered several Saturnian satellites and ring features (including the Cassini division) in the period 1671–1685. The Titan atmospheric *Probe* is named after the Dutch astronomer Christiaan Huygens who discovered Titan in 1655. Portraits of these two scientists are shown in Figure 1.

The seventeenth century was a time of great scientific advances. Modern science was born and mankind's view of the cosmos underwent the most rapid period of change since the beginning of recorded history. Giovanni Domenico Cassini (1625–1712) and Christiaan Huygens (1629–1695) helped to usher in the age by showing the incredulous public the new wonders of the sky, and of science. They changed our perception of the world. Both Cassini and Huygens came from well-to-do families – one in Italy, the other in Holland. Both received the best education available, both were extraordinarily industrious, and both performed most of their work in Paris, as members of the Royal Academy of Sciences established in 1666 by Louis XIV, the fabled Sun King. Huygens earned the invitation to join the Academy and the associated Royal Observatory as a result of having discovered

TABLE I

History of the study of the Saturnian system

| | |
|---|---|
| ∼800 BC | Assyrian and Babylonian observations |
| ∼300 AD | Mythological view of Saturn the god |
| 1610 | Galileo notes the ‘triple planet’ Saturn with his telescope |
| 1655–1659 | Huygens discovers Saturn’s largest satellite, Titan, and the true nature of the rings. |
| 1671–1684 | Cassini discovers a division in the ring, he also discovers the satellites Iapetus, Rhea, Dione and Tethys |
| 1789 | Herschel discovers satellites Mimas and Enceladus and notes thinness of the rings |
| 1848 | Bond and Lassell discover the satellite Hyperion |
| 1850 | Bond, Bond and Daws discover inner ring |
| 1857 | Maxwell proves that rings are not solid |
| 1895 | Keeler measures ring velocities |
| 1898 | Pickering discovers satellite Phoebe |
| 1907 | Comas Sola suggested Titan had an atmosphere |
| 1932 | Wildt discovers methane and ammonia on Saturn |
| 1943–1944 | Kuiper discovers methane and ammonia on Titan |
| 1979 | *Pioneer 11* flies past Saturn |
| 1980 | *Voyager 1* encounters Saturn |
| 1981 | *Voyager 2* encounters Saturn |
| 1989 | Hubble Space Telescope’s Wide Field and Planetary Camera images Saturn |
| 1995 | Hubble Space Telescope’s Wide Field and Planetary Camera-2 images ring plane crossing |
| 1996 | Hubble images indicate that Titan’s surface is heterogeneous |
| 1997 | *Cassini-Huygens* launches |
| 2004 | *Cassini-Huygens* enters Saturn orbit, *Huygens* explores Titan |
| 2005 | *Huygens* Explores Titan |

Titan and his observations of the rings of Saturn. Before joining the Academy, Huygens also had invented the pendulum clock, the first accurate timekeeping device. While still in Italy, Cassini gained fame by having measured the rotation periods of Jupiter and Mars, and for his extensive observations of the motions of the satellites of Jupiter, bodies that had been discovered by Galileo some fifty years earlier. In Paris, Cassini extended his precise observations to Saturn, discovering the satellites Iapetus, Rhea, Dione, and Tethys and structure in the rings. Towards the end of his life, Huygens returned to Holland where he continued pioneering work in mechanics and optics. Cassini stayed at the Paris Observatory where, in addition to conducting regular astronomical observations, he led the development of the new arts of geodesy and map-making.


*Figure 1.* The spacecraft are named after Giovanni Domenico Cassini (right) and Christiaan Huygens (left). They pioneered the exploration of the heavens in the seventeenth century. In the background on the right is the Paris Observatory under construction.

## 1.2. The origin of the Cassini mission

### 1.2.1. *International Planning*

The complex, cooperative undertaking, which is today's *Cassini/Huygens* mission did not come into being overnight. It was the result of a process of many discussions and much careful planning that spanned many years. The formal beginning was 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[2]. 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. The formation of the Joint Working Group and other significant events in the *Cassini/Huygens* chronology are listed in Table II. As can be seen from the chronology, the partners were cautious and did not enter lightly into the decision to carry out the *Cassini/Huygens* mission. Their perception was that this mission would be beneficial for the scientific, technological, and industrial sectors of their countries. The end result was an enterprise that from the initial vision to the completion of its nominal mission will have spanned thirty years!

The *Cassini/Huygens* mission is a joint undertaking by the National Aeronautics and Space Administration (NASA) in the United States and the European Space Agency (ESA). The overall mission is managed by the Jet Propulsion Laborat-

TABLE II
Cassini/Huygens chronology

| Date | Event |
|---|---|
| 1982 | The Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Sciences form a joint working group to study possible U.S. and European cooperation in planetary science. |
| | European scientists D. Gautier and W. Ip propose a combined Saturn *Orbiter* and Titan *Probe* mission to the European Space Agency (ESA) in response to a call for mission proposals. They suggest that the mission be carried out in collaboration with NASA. |
| 1983 | The Solar System Exploration Committee (SSEC) recommends NASA include a Titan *Probe* and radar mapper in its core program and should also consider a Saturn *Orbiter*. |
| 1984–1985 | Joint NASA/ESA assessment study of a Saturn *Orbiter*/Titan *Probe* mission. |
| 1986 | ESA's Scientific Program Committee approves *Cassini* for Phase A study, with a conditional start in 1987. |
| 1987–1988 | NASA carries out further definition and work on the Mariner Mark 2 spacecraft and on the missions designed to use it: CRAF and *Cassini*. |
| | Titan *Probe* Phase A study. |
| | Start development of the facility instruments (ISS (J. Veverka), VIMS (T. McCord), RSS (C. Hamilton)) with advice and oversight by the CRAF scientific teams. |
| 1989 | Funding for CRAF and *Cassini* approved by Congress. |
| | ESA selects *Cassini* mission and names *Probe Huygens*. |
| | NASA and ESA release announcements of opportunity to propose scientific investigations for the Saturn *Orbiter* and Titan *Probe*. |
| | Selection of *Orbiter* and *Probe* investigations. |
| 1991 | NASA AO for INMS as a facility instrument. Selection of INMS investigations. |
| 1992 | Funding cap on CRAF/*Cassini*; CRAF canceled and *Cassini* mission restructured to reduce costs. Launch rescheduled from 1996 to 1997. ISS, VIMS, and RSS become *Cassini* only instruments. |
| 1995 | House appropriations subcommittee targets *Cassini* for cancellation; the action is reversed. |
| 1996 | Integration and testing of spacecraft and instruments. |
| April 21, 1997 | Ship *Cassini* spacecraft to Cape Canaveral, Florida |
| | Start of launch campaign. |
| 1997 | Final integration and testing. |
| October 1997 | Launch from Cape Canaveral, Florida. |

TABLE II
Continued

| Date | Event |
|---|---|
| April 1998 | First Venus gravity-assist flyby. |
| June 1999 | Second Venus gravity-assist flyby. |
| August 1999 | Earth gravity-assist flyby. |
| December 2000 | Jupiter gravity-assist flyby. |
| December 2001 | First gravitational wave experiment. |
| June 12, 2004 | Phoebe flyby. Closest approach is 2 000 km. |
| July 1, 2004 | Arrival at Saturn. Saturn orbit insertion. |
| December 25, 2004 | Release of *Huygens Probe* to Titan. |
| January 14, 2005 | *Huygens* enters Titan's atmosphere. Start of orbital tour of the Saturnian system. |
| July 2008 | Nominal end of mission. |

ory (JPL), Pasadena, California. The *Huygens Titan Probe* was supplied by ESA (Clausen *et al.*, 2002) while the main spacecraft, or *Saturn Orbiter* was provided by NASA (Henry, 2002). The Italian space agency (Agenzia Spaziale Italiana, or ASI), also a partner through a bilateral agreement with NASA, provided hardware systems for the *Orbiter* as well as instruments for both the *Orbiter* and the *Probe.* Other instruments on both the *Orbiter* and the *Probe* were provided by scientific groups, and/or their industrial partners, supported by NASA and by the national funding agencies of member states of ESA (Lebreton and Matson, 2002). The launch vehicle and launch operations were provided by NASA. NASA is also providing the mission operations and telecommunications via the Deep Space Network (DSN). *Huygens* operations are carried out by ESA from its European Space Operations Center (ESOC) in Darmstadt, Germany.

The objectives for the mission and the implementation approach were developed further by the work of the Joint NASA/ESA Assessment Study[3] that was carried out in mid-1984 through 1985. This study group brought the scientific objectives for *Cassini/Huygens* into their present form and published them in the group's final report (ESA, 1985). These objectives then became formally established when they were incorporated into both the NASA and ESA Announcements of Opportunity (ESA, 1989; NASA, 1989, 1991).

### 1.2.2. *The Selection Process*

Prior to the issuance of the Announcements of Opportunity, NASA and ESA carried out an informal dialogue regarding organization and management of the *Cassini/ Huygens* mission. These understandings were formalized in a memorandum

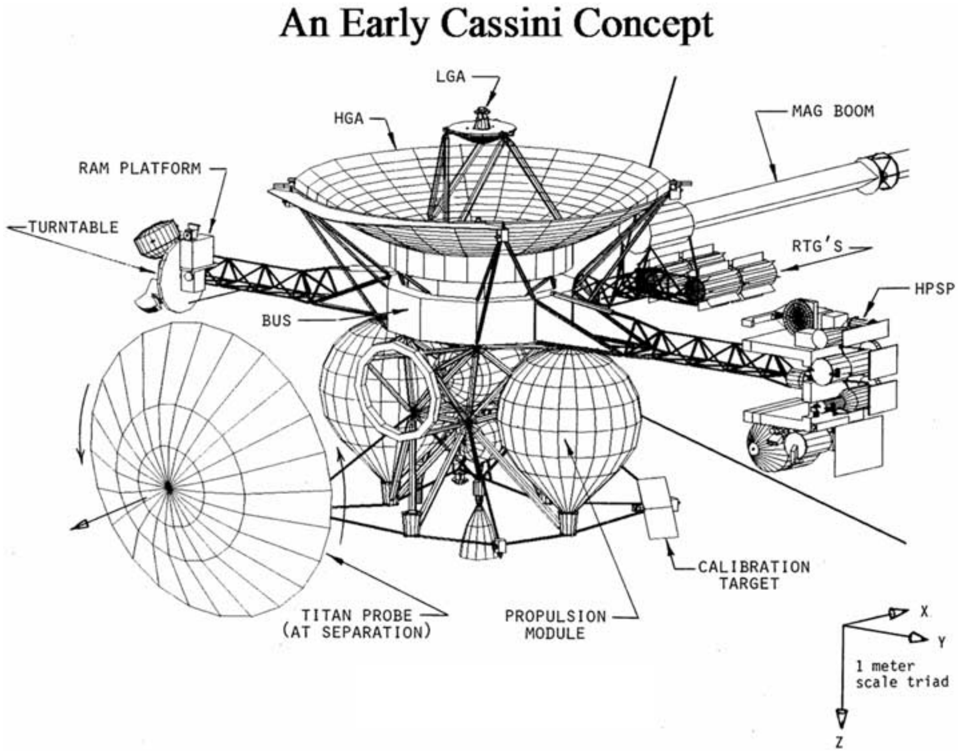


*Figure 2.* A drawing of the first design for *Cassini.* Many of its features were expensive and did not survive the 1992 budget constraints.

of understanding between the agencies. The present organization of the mission evolved from this memorandum.

The selections of 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 those selected for the Saturn Orbiter 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 NASA Saturn *Orbiter* selection was comprised of seven PI-instruments, four facility instruments, and seven IDS investigations. Absent from the proposed instruments was one capable of measuring the properties of the upper reaches of Titan's atmosphere through which *Cassini* would fly many times. Such an instrument was regarded as critical to the mission, both from the scientific and engineering perspectives. NASA decided that such an instrument would be provided as a facility. Thus in May 1991 NASA issued a second Announcement of Opportunity. This one was for the Ion and Neutral Mass Spectrometer (INMS) Team Leader and Team Member positions. The results of that selection were announced in February 1992, bringing the facility instrument count to five. Summaries of the investigations are shown in Tables III and

IV. The corresponding instrumental techniques and measurements are summarized in Tables V and VI.

The originally envisioned *Cassini* and *Huygens* spacecraft were to be optimum for making various types of measurements. While the main spacecraft (*Orbiter*) would be 3-axis stabilized, the instruments would be accommodated by a ram platform, a turntable, an optical calibration target, and a scan platform. A separate steerable antenna would be provided for the communications link with *Huygens* allowing the *Orbiter* remote sensing instruments to observe the entry of *Huygens* into Titan's atmosphere. Figure 2 shows a sketch for this early, ambitious design. Unfortunately, these features did not survive through the development phase of the spacecraft. In early 1992, the *Cassini* project was required to meet a new set of NASA budgetary constraints. The team at JPL reconfigured the mission and the *Saturn Orbiter.* As a result, engineering complexity has been traded for later operational complexity. At the same time the scientific objectives for targets of opportunity (asteroid flyby, Jupiter flyby, and cruise science (NASA, 1989, 1991; Lebreton, 1991)) were given up. This was part of an effort to control development costs and the cost of operation during the first few years in flight. A new plan was established in which the start of scientific data acquisition would wait until two years before arrival at Saturn, i.e., well after the Jupiter flyby.

Fortunately the *Cassini/Huygens* spacecraft had a perfect launch and the spacecraft has performed superbly well in flight. The *Cassini/Huygens* team has a high degree of skill in flawlessly carrying out spacecraft maneuvers. Presently they are developing software programs that will enable the operation of the spacecraft with a high degree of efficiency at Saturn. The engineering team is exercising the spacecraft now in order to have all of the routine operations perfected before reaching Saturn. Once in orbit about Saturn the pace of operations will increase greatly and a smoothly operating spacecraft and operations team will be necessary in order to meet the challenge of performing the many scientific observations.

### 1.3. Why go to Saturn and Titan?

In embarking upon this voyage to Saturn we are following a basic, evolutionally nurtured, instinct to *explore our environment.* Whether this exploration results in the discovery of resources, or the recognition of hazards, or merely provides a sense of place or accomplishment, being familiar with our environment has always proved to be beneficial. It is not surprising, therefore, that such exploration is a hallmark of growing, thriving societies. The expeditions that were mounted by the Old World to explore the New World provide recent examples. There are parallels between those now completed voyages of exploration and the voyages in the newly opened era of Solar System exploration. Available technology, skilled labor, possible benefits, costs, risks, and trip duration continue to be the chief considerations in deciding whether or not to undertake these trips. These factors were weighed for

TABLE III

Cassini Saturn orbiter scientific investigations*

| Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
|---|---|---|
| *Cassini* Plasma Spectrometer (CAPS) | D. Young (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 | *In situ* study of ice and dust grains in the Saturn system |
| Composite Infrared Spectrometer (CIRS) | V. Kunde (PI), NASA Goddard Space Flight Center | Temperature and composition of surfaces, atmospheres, and rings within the Saturn system |
| Interdisciplinary Scientist (IDS) – Magnetosphere and Plasma | M. Blanc (IDS), Observatoire MidiPyrénées | Interdisciplinary study of plasma circulation and magnetosphere-ionosphere coupling |
| Interdisciplinary Scientist (IDS) – Rings and Dust | J. Cuzzi (IDS), NASA Ames Research Center | Interdisciplinary study of rings and dust within the Saturn system |
| Interdisciplinary Scientist (IDS) – Magnetosphere and Plasma | T. Gombosi (IDS), University of Michigan | Interdisciplinary study of the plasma environment in Saturn's magnetosphere |
| Interdisciplinary Scientist (IDS) – Atmospheres | T. Owen (IDS), University of Hawaii | Interdisciplinary study of the atmospheres of Titan and Saturn |
| Interdisciplinary Scientist (IDS) – Satellites | L. Soderblom (IDS), US Geological Survey | Interdisciplinary study of the satellites of Saturn |
| Interdisciplinary Scientist (IDS) – Aeronomy and Solar Wind Interaction | D. Strobel (IDS), Johns Hopkins University | Interdisciplinary study of aeronomy in the Titan and Saturn atmospheres |
| Ion and Neutral Mass Spectrometer (INMS) | 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), University of Arizona | Multispectral imaging of Saturn, Titan, rings, and the icy satellites to observe their properties |
| Dual Technique Magnetometer (MAG) | D. Southwood (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 | Global magnetospheric imaging and insitu measurements of Saturn's magnetosphere and solar wind interactions |
| *Cassini* Radar (RADAR) | C. Elachi (TL), Jet Propulsion Laboratory | Radar imaging, altimetry, and passive radiometry of Titan's surface |

TABLE III
Continued

| Investigation/Acronym | Scientist/Affiliation | Brief Objectives |
|---|---|---|
| Radio and Plasma Wave Science (RPWS) | D. Gurnett (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), Jet Propulsion Laboratory | 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), Jet Propulsion Laboratory | Spectral mapping to study composition and structure of surfaces, atmospheres, and rings |

*IDS = Interdisciplinary Scientist; no instrumentation is provided by an IDS, but data from several PI or TL investigations will be used.
PI = Principal Investigator; each PI proposed the team and was responsible for providing the instrumentation for the investigation.
TL = Team Leader; each TL utilizes a facility instrument provided as part of the spacecraft systems; team members were individually selected by NASA.

*Cassini/Huygens*, both in Europe and in the United States, and we jointly decided to go.

In going to Saturn with *Cassini/Huygens* we will also be satisfying a cultural desire to *obtain new knowledge.* This drive is very strong and our society places very high value on knowledge. The resources expended in creating new knowledge through inventions, research, and scholarship are treated as investments. With *Cassini/Huygens* we do not have to wait for our arrival at Saturn. The return of new knowledge has already occurred. The challenge of this mission has resulted in new technological developments and inventions. Some of these have already been spun-off to new applications whose benefits are being realized now. Nevertheless, the main return occurs when *Cassini/Huygens* reaches Saturn. The mission explores a new part of the solar system, but we learn more than just facts about the Saturnian system. By comparing what we learn with complementary information about Earth, we learn how processes behave and can apply that new knowledge across the solar system. The laws of physics and chemistry are the same everywhere. Thus, for example, knowledge gained about the Saturnian magnetosphere or Titan's atmosphere and weather may turn out to have beneficial terrestrial applications.

TABLE IV
Huygens Titan probe scientific investigations*

| 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 |
| Interdisciplinary Scientist (IDS) – Titan Aeronomy | D. Gautier (IDS), Observatoire de Paris-Meudon | Interdisciplinary study of the aeronomy of Titan's atmosphere |
| Interdisciplinary Scientist (IDS) – Titan Atmosphere-Surface Interactions | J. Lunine (IDS), University of Arizona | Interdisciplinary study of Titan atmosphere-surface interactions |
| Interdisciplinary Scientist (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 |

*IDS = Interdisciplinary Scientist; no instrumentation is provided by an IDS, but data from several PI or TL investigations will be used.
PI = Principal Investigator; each PI proposed the team and was responsible for providing the instrumentation for the investigation.

The *Cassini/Huygens* mission also provides other more indirect benefits. By bringing people of different countries together to work toward a common goal, mutual understanding and common values are promoted. The internationality of *Cassini/Huygens* permits a wider range of talented engineers and scientists to apply themselves to the challenges of this mission. In addition to those directly involved, about three quarters of a million people from more than eighty-one different countries have involved themselves directly in this mission by requesting that their signatures and messages be placed aboard *Cassini/Huygens* for the trip to Saturn. For these many reasons, *Cassini/Huygens* can be regarded as an investment, one

TABLE V
Cassini orbiter instrumental techniques and measurements

| Instruments | Participating countries | Measurements | Techniques |
|---|---|---|---|
| Optical remote-sensing instruments | | | |
| Composite Infrared Spectrometer (CIRS) | U.S.A., Aust., Fr., Ger., It., U.K. | High resolution infrared spectra, 10–1400 $cm^{-1}$ | Spectroscopy using 3 interferometric spectrometers |
| Imaging Science Subsystem (ISS) | U.S.A., Fr., Ger., U.K. | Photometric images through filters, 0.2–1.1 $\mu$m. | Imaging with CCD detectors; 1 wide angle camera (61.2 mr fov); 1 narrow angle camera (6.1 mr fov) |
| Ultraviolet Imaging Spectrograph (UVIS) | U.S.A., Fr., Ger. | Spectral images, 55–190 nm, occultation photometry, 2 ms; H and D spectroscopy, 0.0004 nm resolution | Imaging spectroscopy, 2 spectrometers Hydrogen-Deuterium absorption cell |
| Visible and Infrared Mapping Spectrometer (VIMS) | U.S.A., Fr., Ger., It. | Spectral images, 0.35–1.05 $\mu$m (0.073 $\mu$m res.), 0.85–5.1 $\mu$m (0.166 $\mu$m res.); occultation photometry | Imaging spectroscopy, 2 spectrometers |
| Radio remote-sensing instruments | | | |
| RADAR | U.S.A., Fr., It., U.K. | Ku-band RADAR images (13 777.5 MHz); Radiometry, <0.5 K resolution | Synthetic aperture radar; radiometry with a microwave receiver |
| Radio Science Subsystem (RSS) | U.S.A., It. | Ka, S, and X bands; frequency, phase, timing, and amplitude | X- and Ka-band transmissions to *Cassini*; Ka-, S- and X-band transmissions to the Earth |

that is providing both immediate benefits as well as the expectation of many more to come.

### 1.4. Goal and Objectives

*The primary goal of Cassini/Huygens is to 'conduct an in-depth exploration of the Saturnian System'* (NASA, 1989).

Three trail blazing spacecraft, *Pioneer 11*, *Voyagers 1* and *2*, have already visited Saturn. Each flew rapidly through the Saturnian system. They sent back to

TABLE V
Continued

| Instruments | Participating countries | Measurements | Techniques |
|---|---|---|---|
| Particle remote-sensing and *in situ* measurement instrument | | | |
| Magnetospheric Imaging Instrument (MIMI) | U.S.A., Fr., Ger. | Image energetic neutrals and ions $<$10 keV–8 MeV/nucleon; composition.<br>10–265 keV/e ions; charge state; composition; directional flux.<br>20 keV–130 MeV ions; 15 keV to $>$11 MeV electrons; directional flux | Particle detection and imaging. Ion-neutral camera (time of flight, total energy detector)<br>Charge-energy-mass spectrometer<br>Solid state detectors with (1) magnetic focusing telescope, and (2) aperture controlled $\sim 45°$ field of view |
| *In situ* measurement instruments | | | |
| *Cassini* Plasma Spectrometer (CAPS) | U.S.A., Fin., Fr., Hun., Nor. U.K. | Particle energy/charge: 0.7–30 000 eV/e<br>1–50 000 eV/e<br>1–50 000 eV/e | Particle detection and spectroscopy. Electron spectrometer; Ion mass spectrometer; Ion beam spectrometer |
| Cosmic Dust Analyzer (CDA) | Ger., Cz., Fr., Nor., U.K., U.S.A., ESA | Directional flux and mass of dust particles in range of $10^{-16}$ to $10^{-6}$ g | Impact induced currents |
| Dual Technique Magnetometer (MAG) | U.K., Ger., It., U.S.A. | B DC to 4 Hz up to 256 nT. Scalar field DC to 20 Hz up to 44 000 nT | Magnetic field measurement.<br>Flux gate magnetometer; Vector/scalar magnetometer |
| Ion and Neutral Mass Spectrometer (INMS) | U.S.A., Ger. | Fluxes of +ions and neutrals in mass range of 1–66 amu | Mass spectrometry |
| Radio and Plasma Wave Science (RPWS) | U.S.A., Aust., Fr., Swed., U.K., ESA | E 10 Hz–2 MHz<br>B 1 Hz–20 kHz<br>Plasma density | Radio frequency receivers.<br>3 electric dipole antennas;<br>3 magnetic search coils;<br>Langmuir *Probe* current |

us eye-opening data. Titan, in particular, was revealed as an entirely new world, a unique object. While we learned much that we did not know, these data also introduced us to many puzzling effects. As a result many new questions have been posed. The early probes did not give us a good understanding of Titan, or of many other elements of the system. An in-depth study was in order.

TABLE VI

Huygens instrumental techniques and measurements

| Instruments | Participating countries | Measurements | Techniques |
|---|---|---|---|
| *Huygens* Atmospheric Structure Instrument (HASI) | It., Aust., Ger., Fin., Fr., Nor., Sp., U.S.A., U.K., ESA | Temperature: 50–300 K. Pressure: 0–2000 mbar. Gravity: 1 $\mu$g–20 mg AC *E*-field: 0–10 kHz, 80 dB at 2 $\mu$Vm$^{-1}$ Hz$^{-0.5}$ DC *E*-field: 50 dB at 40 mV/m Electrical conductivity: $10^{-15}\Omega$/m to $\infty$ Relative permittivity: 1 to $\infty$ Acoustic: 0–5 kHz, 90 dB at 5 mPa | Direct measurements using 'laboratory' methods. |
| Gas Chromatograph and Mass Spectrometer (GCMS) | U.S.A., Aust., Fr., | Mass range: 2–146 amu Dynamic range: $>10^8$ Sensitivity: $10^{-12}$ mixing ratio Mass resolution: $10^{-6}$ at 60 amu | Chromatography and mass spectrometry: 3 parallel chromatographic columns; quadrapole mass filter; 5 electron impact sources |
| Aerosol Collector and Pyrolyzer (ACP) | Fr., Aust., U.S.A. | 2 samples: 150–45 km, 30–15 km altitude | 3 step pyrolysis: 20 °C, 250 °C, 650 °C |
| Descent Imager and Spectral Radiometer (DISR) | U.S.A., Ger., Fr. | Upward and downward spectra: 480–960 nm, 0.87–1.7 $\mu$m, resolution 2.4–6.3 nm; down-ward and side-looking images: 0.66–1 $\mu$m; solar aureole photometry, 550 nm, 939 nm; surface spectral reflectance | Spectrophotometry, imaging, photometry, and surface illumination by lamp. |
| Doppler Wind Experiment (DWE) | Ger., It., U.S.A. | (Allan Variance)$^{1/2}$: $10^{-11}$ (in 1 s), $5 \times 10^{-12}$ (in 10 s), $10^{-12}$ (in 100 s), corresponding to wind velocities of 2 m/s to 200 m/s, *Probe* spin | Doppler shift of *Huygens* telemetry signal, signal attenuation |
| Surface Science Package (SSP) | U.K., It., U.S.A., ESA | Gravity: 0–100 g. Tilt: $\pm 60°$. Temperature: 65–100 K. Thermal conductivity: 0–400 mW m$^{-1}$ K$^{-1}$. Speed of sound: 150–2000 m/s. Liquid density: 400–700 kg m$^{-3}$. Refractive index: 1.25–1.45 | Impact acceleration; acoustic sounding, liquid relative permittivity, density and index of refraction |

With the dedication of the *Galileo* mission to the Jovian system, Saturn became the next logical target. Not only would this new mission study the individual objects (i.e., planet, satellites, rings, and magnetosphere) but it also would study the interactions between and among them.

#### 1.4.1. *System Science*

The list of scientific objectives for *Cassini/Huygens* is extensive. There are specific objectives for each of the types of bodies in the system – the planet itself, the rings, Titan, icy satellites, and the magnetosphere. Not only is *Cassini/Huygens* designed to determine the present state of these bodies, and the processes operating on or in them, but it is also equipped to discover the interactions that occur among them. These interactions are important. An analogy can be drawn to a *mechanical clock.* A *clock* has many parts. However, a description of each part and the cataloging of their mechanical properties, alone, completely misses the essence of a *clock. The essence is in the interactions between the parts.* So it is for much of what *Cassini/Huygens* will be studying in the Saturnian system.

The ability to do ‘system science’ sets the superbly instrumented spacecraft apart. The very complex interactions that occur in systems such as those found at Jupiter and Saturn can only be addressed by such instrument sets. This is because many of the phenomena to be studied are sensitive to a large number of parameters. There are well known examples where the measurement being made is simultaneously dependent upon *location*, *time*, *directions to the sun and planet*, the *orbital* configurations of certain satellites, *magnetic longitude* and *latitude*, and *solar wind properties.* To deal with such complexity, it is necessary that the spacecraft have the right types of instruments in order to make all of the necessary measurements and that those measurements be made simultaneously. Identical conditions very seldom, if ever, recur.

Requiring that the instruments be able to operate simultaneously has a major impact upon spacecraft resources, such as electrical power. This requirement plus the need for a broad-based, diverse collection of instruments sized to be able to detect the low densities and weak signals of the Saturn environment is the reason why the *Cassini/Huygens* spacecraft is one of the largest planetary spacecraft to date.

## 2. Scientific Objectives

The lineage of the *Cassini/Huygens* objectives can be traced back to the meetings of the Joint Working Group in 1982. Objectives were established for the planet, the rings, the magnetosphere, the icy satellites and Titan.

## 2.1. SATURNIAN SYSTEM OBJECTIVES IN THE NASA AND ESA ANNOUNCEMENTS OF OPPORTUNITY

The list of scientific objectives covers the present state of these bodies, the processes operating on or in them and the interactions that occur among and between them. The objectives judged to be of the highest level in importance were part of both the NASA and ESA Announcements of Opportunity for this mission and were the criteria against which the selected investigations were measured. They also have provided the standard against which priorities for taking data were set. The objectives in the following lists are not prioritized and no significance that should be attached to the order of their appearance.

### 2.1.1. *Titan*

Titan is the major focus of the mission. It will be studied by both the *Huygens Probe* and the *Cassini Orbiter.* The scientific objectives are to:
- 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.
- 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;
- Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges;
- Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite;
- Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

While the formal set of scientific objectives is the same for both *Probe* and *Orbiter*, several additional constraints apply with respect to the synergistic gathering of data. 'In the design of the *Huygens* measurements and *Orbiter* observations it is highly desirable that the value of the whole set of data be maximized'. To strive for this synergistic effect, there are some specific objectives that have been identified:
- 'Each time the *Orbiter* will fly by Titan, it will perform a set of atmosphere and surface remote-sensing observations which will include re-observations of the atmosphere and surface along the flight path of the *Probe*.
- In this respect the *Probe* data will provide a reference set of data which will be used to 'calibrate' the Orbiter observations. The *Probe* data will be used, together with the *Orbiter* data, for studying spatial and seasonal variations of the atmosphere composition and dynamics.'

(ESA, 1989).

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Lebreton and Matson (2002).

Titan has interesting modes of interaction with its immediate environment which can have two different states. The size and shape of the Saturnian magnetosphere depends upon the pressure of the solar wind. An increase in the solar wind pressure pushes the front of the magnetosphere (i.e., bow shock, magnetopause) closer to Saturn and visa versa. Titan's orbit passes through the region over which these changes occur. When Titan is at inferior conjunction (as seen from the Sun) it may be either inside or outside of the magnetosphere. The interaction with its plasma environment should be quite different in these two situations. Understanding how Titan interacts with its varying environment is an objective of the working group on the magnetosphere, atmosphere and plasma science (MAPS) (Blanc *et al.*, 2002).

### 2.1.2. *Magnetosphere*

Specific *Cassini* objectives for magnetospheric and plasma science are to:

- Determine the configuration of the nearly axially symmetric magnetic field and its relation to the modulation of Saturn Kilometric Radiation (SKR).
- Determine current systems, composition, sources, and sinks of magnetosphere charged particles.
- 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.
- Study the effect of Titan's interaction with the solar wind and magnetospheric plasma.
- Investigate interactions of Titan's atmosphere and exosphere with the surrounding plasma.

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Blanc, *et al.* (2002). In addition the icy satellites have interesting interactions with the magnetosphere. Not only do they absorb particles from the magnetospheric plasma, but they can also contribute material to the magnetosphere. Furthermore, upon their solid surfaces are written their histories and by extrapolation that for much of the Saturnian system.

### 2.1.3. *Icy Satellites*

The known icy satellites have radii from 10 to 765 km. Over this size range different processes operate and the relative importance of some of the processes is a function of the satellite's size. Thus the satellites provide good examples for studying how such bodies are formed and evolve. Apart from their intrinsic interest, the icy satellites (and Titan) record the geologic history of the system through the records that have been 'written' on their surfaces by impacting objects. Specific *Cassini* objectives for icy satellite science are to:

- Determine the general characteristics and geological histories of the satellites.
- Define the mechanisms of crustal and surface modifications, both external and internal.
- Investigate the compositions and distributions of surface materials, particularly dark, organic rich materials and low melting point condensed volatiles.
- Constrain models of the satellites' bulk compositions and internal structures.
- Investigate interactions with the magnetosphere and ring systems and possible gas injections into the magnetosphere.

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Lunine and Soderblom (2002). As satellites become smaller they start to approach the size domain of ring particles. In fact, some of the smaller icy satellites are embedded in the rings. There they define resonances and participate in other phenomena that establish the ring structures we observe.

#### 2.1.4. *Saturn's Ring System*

Saturn has by far the best-developed ring system in the solar system. Knowledge gained by studying these rings will be applicable to ring systems and planetary disks that occur elsewhere in the universe. Specific *Cassini* objectives for ring science are to:

- Study configuration of the rings and dynamical processes (gravitational, viscous, erosional, and electromagnetic) responsible for ring structure.
- Map composition and size distribution of ring material.
- Investigate interrelation of rings and satellites, including imbedded satellites.
- Determine dust and meteoroid distribution in the vicinity of the rings.
- Study interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere.

A discussion of these requirements, as well as some more specific objectives that can be derived from them, can be found in the article by Cuzzi *et al.* (2002).

#### 2.1.5. *Saturn*

Jupiter and Saturn provide examples of objects in the large-planetary size range that, presumably, occur throughout the universe. Saturn is known to be very different from Jupiter. We have the opportunity to study Saturn's properties with *Cassini.* The rotationally axisymetric magnetic field arising from inside governs the magnetosphere and participates in all of the interactions with the other elements of the system. Finally, completing the circle of interactions, the energetic particles in the magnetosphere crash into Saturn's atmosphere giving rise to aurora. Specific *Cassini* objectives for Saturn are to:

- Determine temperature field, cloud properties, and composition of the atmosphere of Saturn.
- Measure the global wind field, including wave and eddy components; observe synoptic cloud features and processes.

- Infer the internal structure and rotation of the deep atmosphere.
- Study the diurnal variations and magnetic control of the ionosphere of Saturn.
- Provide observational constraints (gas composition, isotope ratios, heat flux, etc.) on scenarios for the formation and the evolution of Saturn.
- Investigate the sources and the morphology of Saturn lightning (Saturn Electrostatic Discharges (SED), lightning whistlers).

A discussion of these requirements as well as some more specific objectives that can be derived from them can be found in the article by Owen and Gautier (2002).

### 2.2. Further development of objectives by the Project Science Group

Further development of the AO scientific objectives for *Cassini/Huygens* has been carried out by the Project Science Group (PSG) and the *Huygens* Science Working Team (HSWT). These groups, chartered by the AOs, are the Program's scientific advisory bodies. They work on specifying more detail than embodied in AO requirements themselves and in keeping the requirements up to date with respect to any new developments. In the PSG this work was done by a set of committees called Discipline Working Groups (DWG) specializing in each set of requirements and co-chaired by Interdisciplinary Scientists as was envisioned in the AO. The results of their work can be found in later articles in this volume: 'Cassini-Huygens Investigations of Satellite Surfaces and Interiors', 'Saturn's rings: Pre-Cassini Status and Mission Goals', 'Magnetospheric and Plasma Science with Cassini-Huygens', and 'Touring the Saturnian System: The Atmospheres of Titan and Saturn'.

The PSG and the HSWT also have the responsibility to translate the requirements into strategies for observing and measuring. The workload is shared by the four DWGs, special working groups, and instrument scientific investigation teams under the direction of the PIs and TLs. The strategies are, in turn, translated into specific instrumental observations and measurements by the scientists and the engineering and operations staffs of the individual instruments. All of these steps are closely coordinated with the spacecraft operations staffs at JPL and ESOC (for *Huygens* instruments).

## 3. Cassini and Huygens Spacecraft

### 3.1. The Cassini orbiter spacecraft

At the time of launch, the mass of the fully fuelled spacecraft was about 5636 kg. As shown in Figures 3 to 5, *Cassini* consists of several sections. Starting at the bottom of the 'stack' and moving upward, these are the *lower equipment module*, the *propellant tanks* together with the *engines*, the *upper equipment module*, *the twelve-bay electronics compartment*, and the *high-gain antenna* (HGA). These are all stacked vertically on top of each other. Attached to the side of the stack is an approximately three-meter diameter, disk-shaped spacecraft, the *Huygens Probe. Cassini/Huygens* accommodates some twenty-seven different scientific investigations which are supported by eighteen specially designed instruments, twelve on the *Orbiter* and six on the *Huygens Probe.* (These investigations are listed in Tables V and VI. Also, see the more detailed discussions of the *Orbiter* instruments which comprises the second volume of this series). Most of the *Orbiter*'s scientific instruments are installed on one of two body-fixed platforms. These are called the *remote-sensing pallet* and the *particles-and-fields pallet.* The 11-meter-long boom supports sensors for the Dual Technique Magnetometer (MAG) experiment. Three skinny, ten-meter-long, electrical antennae point in orthogonal directions. These are sensors for the *Radio and Plasma Wave Science* (RPWS) experiment. At the top of the stack is the large, 4-meter-diameter *high-gain antenna.* Centered and at the very top of this antenna is a relatively small *low-gain antenna.* Another *low-gain antenna* is located near the bottom of the spacecraft.

Electrical power for the *Cassini* spacecraft and instruments is provided by three *Radioisotope Thermoelectric Generators* (RTG). RTGs are lightweight, compact spacecraft power systems that are extraordinarily reliable. They are not nuclear reactors and they have no moving parts. They provide electrical power through the natural radioactive decay of plutonium (Pu-238, a non-weapons-grade isotope). The heat generated by this natural process is changed into electricity by solid-state thermoelectric converters. A drawing of a *Cassini* RTG is shown in Figure 6.

RTGs have provided electrical power for some of the space program's greatest successes, including the *Apollo* lunar landings and the *Viking* landers on Mars. RTGs made possible the *Voyager* explorations of Jupiter, Saturn, Uranus and Neptune, as well as the *Pioneer* missions to Jupiter and Saturn. RTG power sources are enabling the *Galileo* mission to Jupiter and the international *Ulysses* mission studying the Sun's polar regions. The *Cassini* mission, given its scientific objectives, available launch systems, travel time to its destination and Saturn's extreme distance from the Sun, required the use of three RTGs.

The temperatures of the various parts of the spacecraft are maintained within their required values by several means: (1) insulation and blankets, (2) reflective coatings, (3) shade provided by other parts of the spacecraft, (4) heat produced by the normal operation of the device, (5) electric heaters, and (6) small, radio-isotope heaters.

Two-way communication with *Cassini* is through the Deep Space Network (DSN) via an X-band radio link, which uses either the 4-meter-diameter high-gain antenna (HGA), or one of the low gain antennae. The high-gain antenna is also used for radio and radar experiments and for receiving signals from *Huygens.* At Saturn, communications will be via the HGA.

*Cassini* is a three-axis-stabilized spacecraft. Either reaction wheels or the set of 0.5 N (Newton) thrusters can change the attitude of the spacecraft. Attitude changes will be done frequently because the instruments are body-fixed and the

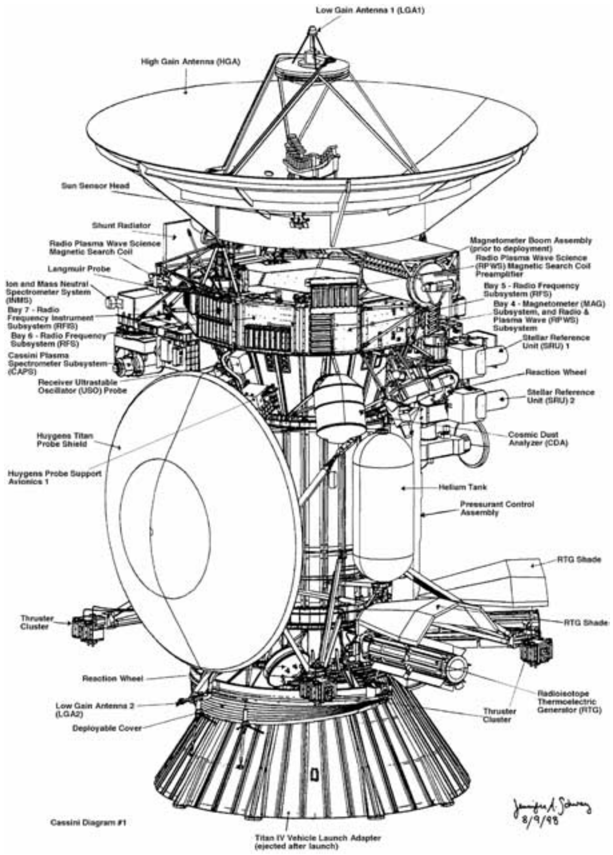


*Figure 3.* The *Cassini* spacecraft. At the top is the high-gain antenna that is 4 m in diameter. The structure at the bottom is the adapter that attaches the spacecraft to the launch vehicle. It is jettisoned after launch.

whole spacecraft must be turned in order to point them. Consequently, most of the spacecraft activities are made without a real-time communications link to Earth. The data are recorded on two solid-state recorders, each of which has a storage capacity of about two gigabits.

The Solid State Recorder (SSR) is the primary data storage and retrieval device for the *Orbiter.* The spacecraft is equipped with two SSRs each of which is expected to have a usable capacity of 1.8 Gigabits at end of mission. The nominal effects of solar and cosmic radiation have been taken into account when estimating the end of mission capacity. The SSR will store spacecraft telemetry and Attitude Articulation and Control (AACS), Command and Data Subsystem (CDS), and instrument memory-loads in separate partitions. All data recorded on and played back from the SSR is handled by the CDS.

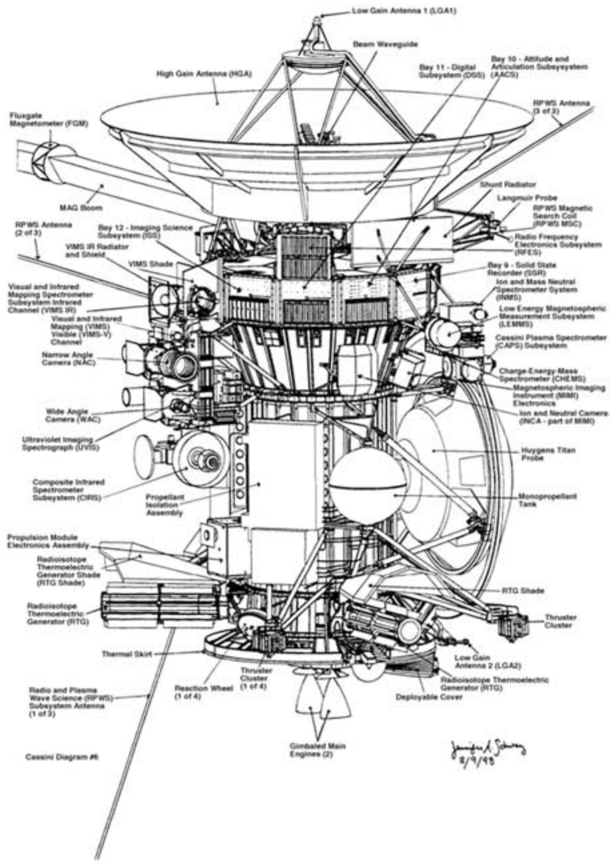


*Figure 4.* The *Cassini* spacecraft (looking from a position about half way between the +X and −Y axes, and slightly above in the −Z direction).

### 3.2. THE HUYGENS TITAN PROBE

The *Huygens Titan Probe* is destined for entry into Titan's atmosphere. It carries a capable, diverse, set of instruments for measuring atmospheric and surface properties. The *Huygens Probe* System also has another part, the *Probe Support Equipment* (PSE), which is permanently attached to the *Cassini Orbiter.* The PSE includes a *spin-eject device* that releases a strong spring-loaded mechanism that simultaneously propels the *Probe* away from the *Orbiter* and imparts to it a spin about its axis of a little more than 5 rpm. Separation occurs with a relative velocity of 0.3 to 0.4 m/s. Altogether, the *Probe* weighs about 305 kg and the *Probe* Support Equipment is only about 35 kg. *Huygens* is a very bluntly shaped conical capsule with a high drag coefficient. It consists of a *descent module* that is enclosed by a *thermal-protection shell* to protect the *Probe* from the heat generated during atmospheric entry.

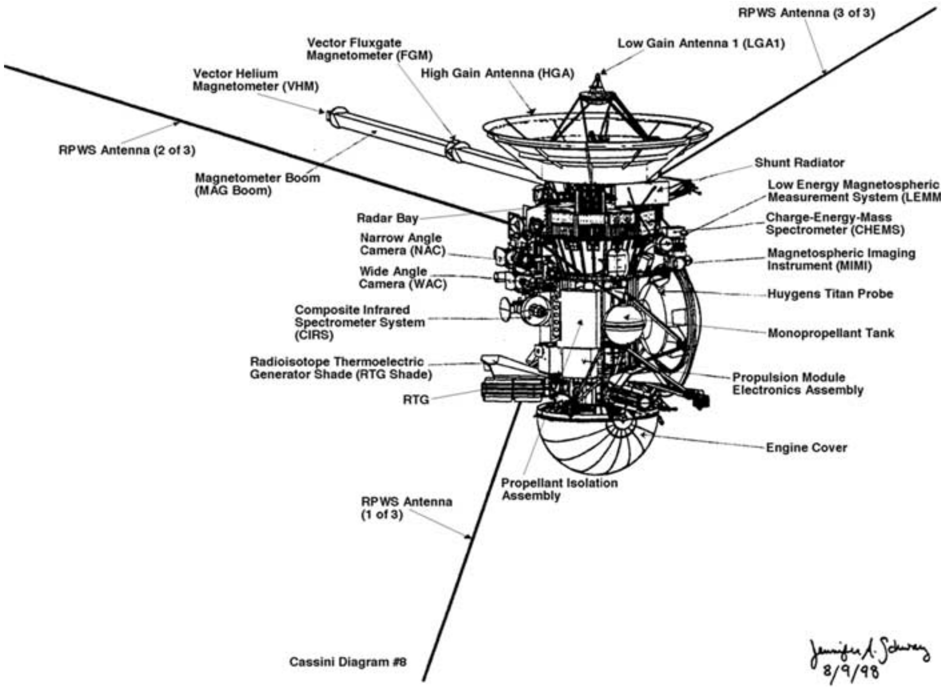


*Figure 5.* The *Cassini* spacecraft (view as in Figure 4) showing the engine cover deployed. This cover protected the nozzles from micrometeorites during the transit of the asteroid belt.

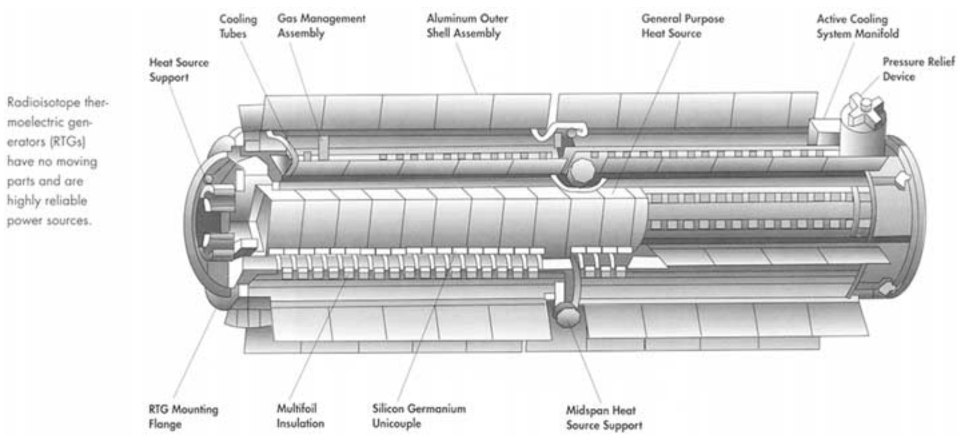


*Figure 6.* Cut-away drawing of a Radioisotope Thermoelectric Generator (RTG). Three of these provide electricity for the thousands of tasks that *Cassini* will perform at Saturn.

The *Probe Data Relay Subsystem* (PDRS) provides the one-way communications link between the *Probe* and the *Orbiter* and includes equipment installed on both spacecraft. The elements that are part of the PSE are the *Probe Support Avionics* (PSA) and the *Radio Frequency Electronics* (RFE) which includes an *ultra-stable oscillator* (USO) and a low-noise amplifier. For redundancy, the *Probe* carries two S-band transmitters, both of which transmit during descent, each via its own antenna. The telemetry in one link is delayed by about six seconds with respect to the other link in order to avoid loss of data if there should be brief transmission outages. Reacquisition of the *Probe* signal would normally occur within this interval.

### 3.3. Flight operations

The flight operations of the *Cassini* mission operations are carried out at Mission Control Center, Jet Propulsion Laboratory (JPL) in Pasadena, California. The data are collected via NASA's deep space network and stored on computers at JPL. The spacecraft health and status are routinely assessed. The operations of the *Cassini* instruments are distributed. The instrument teams analyze their respective instrumental data and prepare instrumental operation sequences at their home institution and transmit them to JPL for uplink. During the main mission phase, from the start of the Saturn encounter phase until the end of the mission, the *Orbiter* instrument teams will interact daily with the team at JPL. The flight operations of the *Huygens Probe* are carried out from ESA's European Operations Centre (ESOC) in Darmstadt, Germany. Here the *Huygens* Probe Operations Centre (HPOC) has been established. All *Huygens*-related mission activities are carried out from the HPOC (e.g., periodic in-flight checkouts, communication equipment characterization and testing, and software modification and testing). When the *Huygens* telemetry returns it will be routed to the HPOC, where it will be 'decoded' to retrieve the instrument data which will be sent to the appropriate *Huygens* investigators.

## 4. Scientific Instruments

*Cassini/Huygens* accommodates some twenty-seven major scientific investigations that, in turn, are supported by eighteen specially designed instruments, twelve on the *Orbiter* and six on the *Huygens Probe.* A drawing showing how some of the probe instruments are packaged on the *Huygens* instrument platform is shown in Figure 7. Other instruments are attached on the bottom side of this platform. Lebreton and Matson (2002) present more detail on the Probe payload in a following article.

The *Cassini Orbiter* has the most capable and sophisticated set of instruments of any spacecraft sent to the outer Solar System. Many of the instruments have multiple detectors, or even several whole instruments as subsystems. Some were

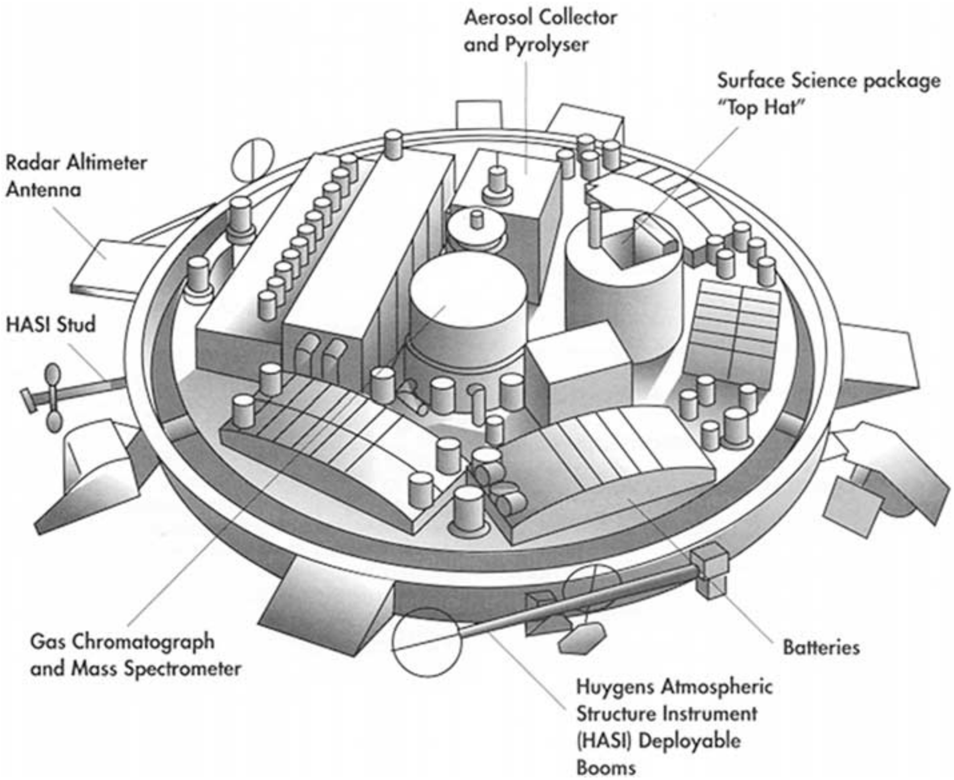


*Figure 7.* A drawing showing the layout of *Huygens'* instruments.

built with articulation capability in order to assure optimum pointing for data acquisition. Compared to earlier spacecraft instruments, many *Cassini* instruments use much broader-bandpass data acquisition. Rather than obtain the spectrum of a spot, for example, they obtain spectra for all the pixels in a whole scene. Rather than measure one or a few energies, or frequencies, they are focused on obtaining the whole spectrum as a function of time. The wavelength ranges of the imaging sensors and the energy ranges of the particle investigations are shown in Figure 8. With few exceptions, all of the instruments will be obtaining large amounts of data, enough to fill Cassini's 4 Gb per day bits-to-Earth capacity during 'high-activity' days.

There are two general classes of instruments on the *Orbiter*, those that make *in situ* measurements and those that carry out remote sensing. The *in-situ* instruments are mounted at several locations on the spacecraft. CAPS, INMS and MIMI are on the fields-and-particles pallet, Figure 9. The CDA, INCA (part of MIMI), and the RPWS components are mounted on the body of the spacecraft. MAG has its own boom. The fields of view, where appropriate, for these instruments are shown in Figures 10 and 11.

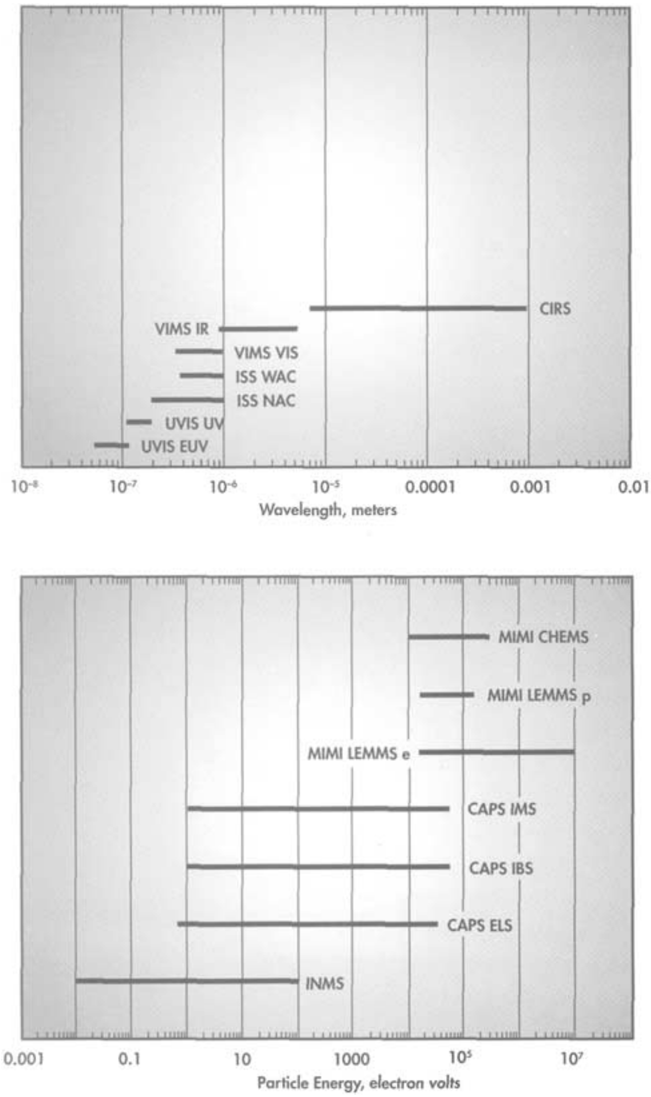


*Figure 8.* The spectral and energy ranges of *Cassini Orbiter* instruments.

The optical remote sensing instruments are mounted on a separate pallet, Figure 12. All of these instruments have built-in telescopes. Their fields of view on the sky are shown in Figure 13. Other remote sensing instruments are the RADAR and the RSS. Of course, these use the high-gain antenna. INCA, already discussed as part of MIMI is also a remote sensing instrument that images ions and neutrals and it is mounted on the body of the spacecraft. Detailed discussions of these instruments can be found in following articles by the instrument teams.

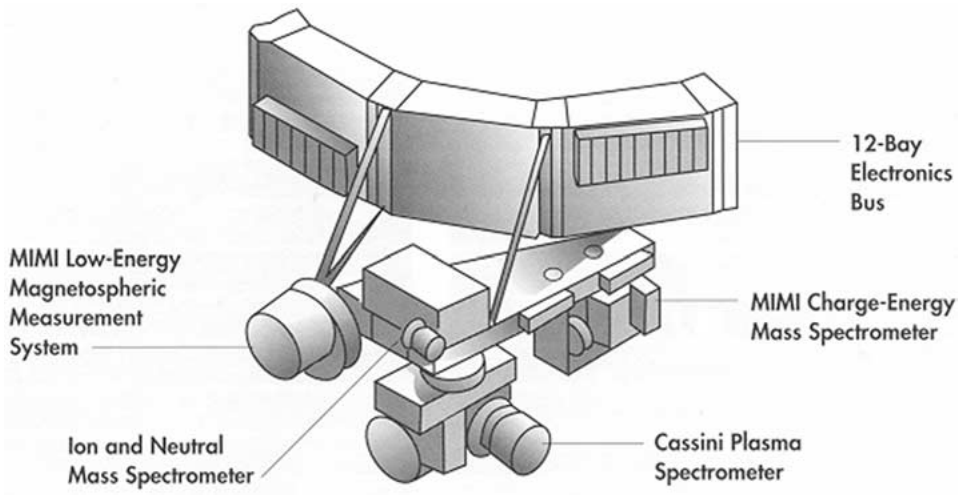


*Figure 9.* The fields-and-particles pallet. This triangular, horizontal structure provides mounting points for most of the fields-and-particles instruments.

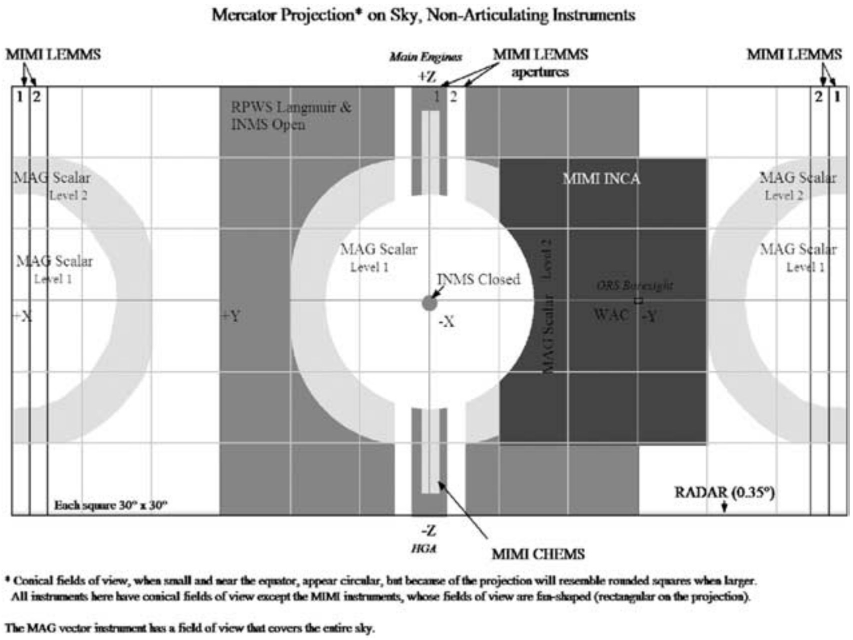


*Figure 10.* The fields of view on the sky for the fixed (i.e., non-articulating) fields-and-particles instruments.

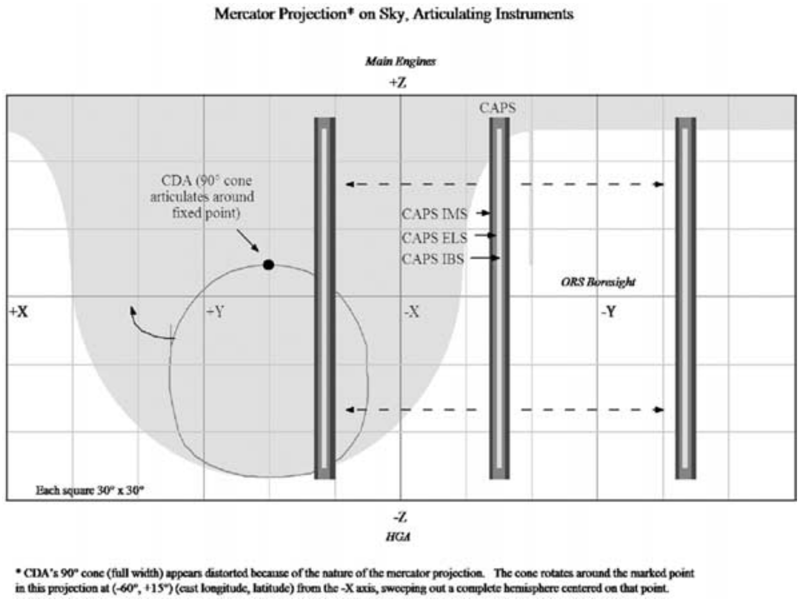


*Figure 11.* The fields of view on the sky for articulating fields-and-particles instruments. Each of these instruments can use a motor to change the pointing of its 'bore sight' or instrumental field of view. All directions which can be viewed are shown in the above plot.

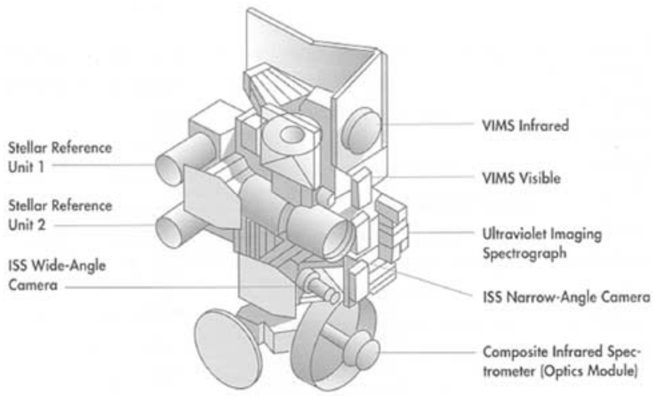


*Figure 12.* The remote sensing pallet is largely obscured by the instruments that it supports. All of the optical remote sensing instruments as well as the star trackers are mounted on this pallet.

## 5. Launch and Cruise Phase

Although *Cassini/Huygens* officially had no cruise science phase, much has been accomplished by the mission on its way to Saturn. At this writing the spacecraft has passed Jupiter and is now on the way to Saturn. We digress for a moment to discuss the journey thus far before returning to the discussion of the objectives to be pursued at Saturn.

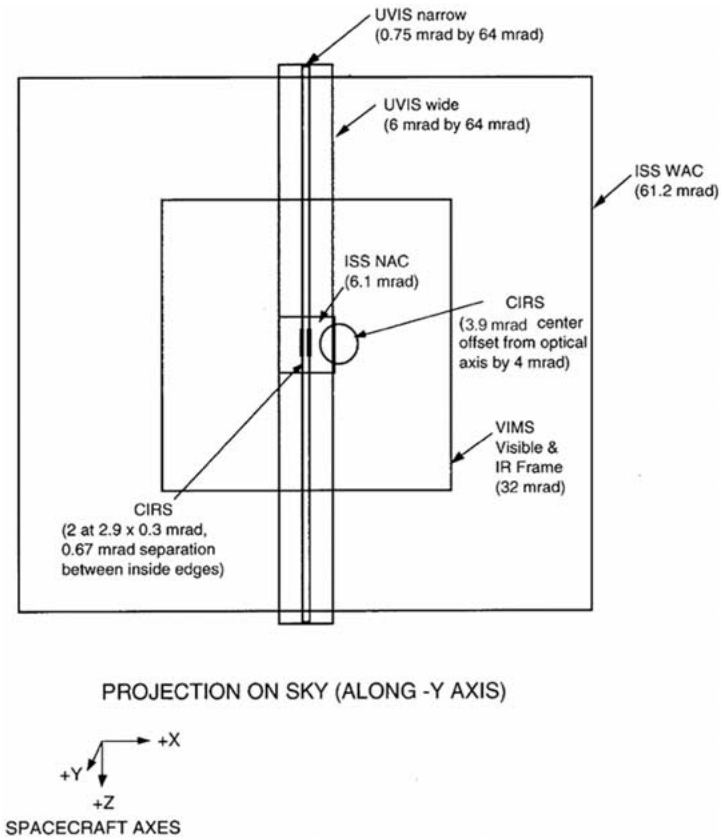


*Figure 13.* The fields of view on the sky for the remote-sensing optical instruments.

## 5.1. Launch

Launch is both an *ending* and a *beginning.* Nowhere can you find a more profound test of the work that has been done. Nowhere is there a more dramatic event to mark changing program priorities. Nowhere is there more hope. Nowhere more tension. A successful launch is *everything.* These were the thoughts of many at the Cape Canaveral Air Force Station on the $15^{th}$ of October, 1997. The launch vehicle was the *Titan IVB* with two stout *Solid Rocket Motor Upgrades* (SRMU) attached to its lower stage. A *Centaur* rocket sat on top of the propulsion stack as the uppermost stage, Figure 14. This system puts *Cassini/Huygens* into Earth orbit and then, at the right time injects it upon its interplanetary trajectory.

The ‘core’ *Titan* vehicle has two stages. The SRMUs are anchored to the first, or lower, stage. These ‘strap-on’ rockets burn solid fuel, whereas the *Titan* uses liquid-fuel. The *Centaur* is a versatile, high-energy, cryogenic-liquid-fueled upper stage with two multiple-start engines. The performance of the *Titan IVB/SRMU-Centaur* system is capable of placing a 5760-kg payload in a geostationary orbit. On top

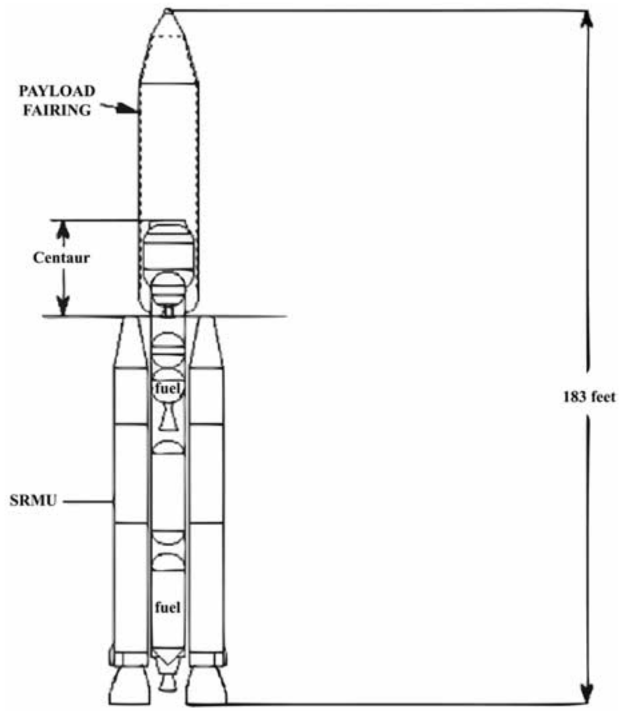


*Figure 14.* A sketch of the Titan 3B-Centaur in launch configuration.

of all this propulsive might sits *Cassini/Huygens*, protected for its trip through the lower atmosphere by a 20-meter-long payload fairing.

Lift-off from Cape Canaveral Air Force Station, launch complex 40 was at night. The launch sequence, shown in Figure 15, began with the ignition of the two SRMUs. They lifted the whole stack off of the pad. About ten seconds after liftoff, the stack continued to accelerate, and then, it started to tilt and rotate. The rotation continued until the required azimuth was reached. At plus two minutes the first stage of the *Titan* was ignited. The altitude was approximately 192 000 feet. A few seconds later the two, now spent, SRMUs were jettisoned. One-and-a-half minutes passed. At an altitude of 360 000 feet, the payload fairing was let go. It was about five and a half minutes into the flight when an altitude of 549 000 feet was reached. The first stage of the *Titan* separated at this altitude and the second stage fired. At launch plus nine minutes the second stage had burnt out and dropped away. Then the *Centaur* ignited and boosted the remaining rocket-and-spacecraft stack into a parking orbit and turned off its engines. Sixteen minutes later the *Centaur* ignited for a second time. The burn lasted between 7 and 8 minutes. Then the *Centaur* separated from the spacecraft. *Cassini/Huygens* was now on an interplanetary trajectory, headed for swingbys of Venus, Venus again, Earth, Jupiter, and at last, orbit about Saturn. It was a perfect launch! The interplanetary trajectory is shown in Figure 16.

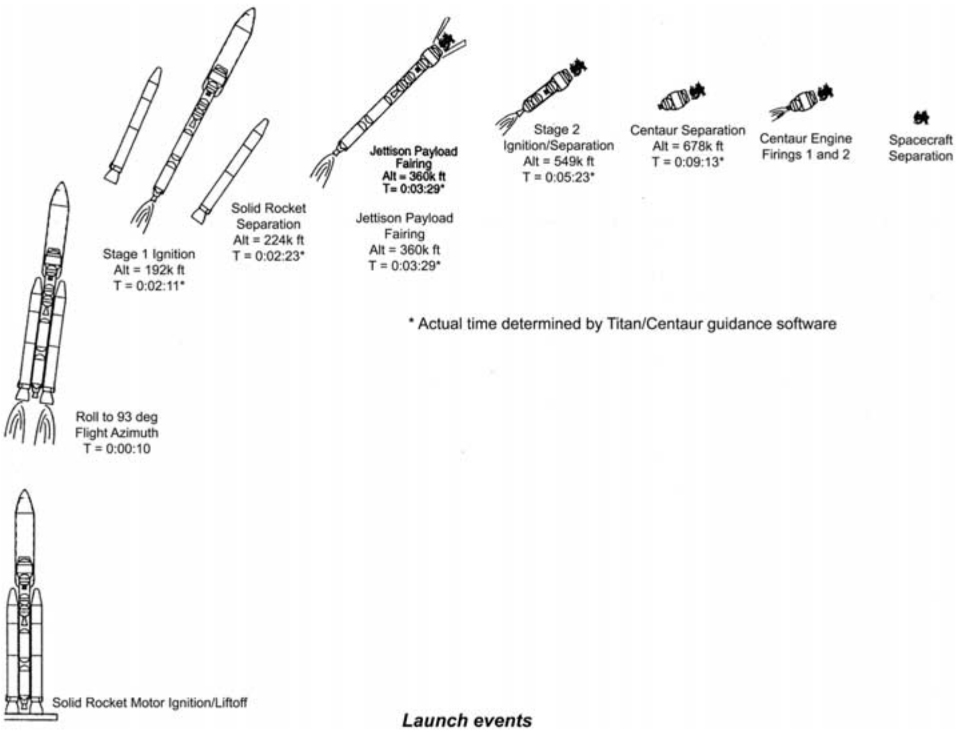


*Figure 15.* The sequence of events for launch in to orbit above Earth.

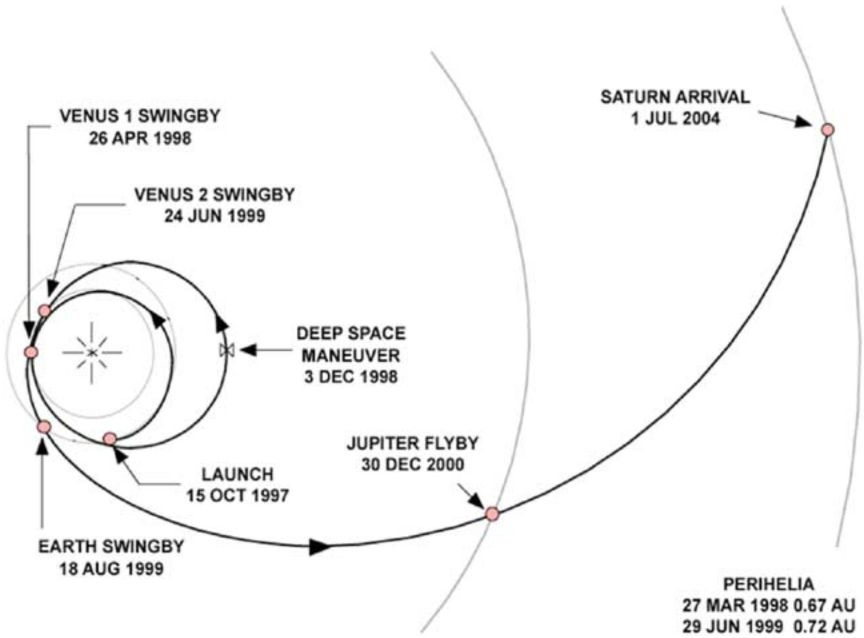


*Figure 16.* The *Cassini* cruise trajectory to Saturn.

TABLE VII
Venus and Earth flybys

| Instrument | Objectives |
|---|---|
| *Venus 1st Flyby* | |
| RPWS | Search for lightning |
| *Venus 2nd Flyby* | |
| CAPS | Ion composition and pickup |
| CDA | Inner Solar System dust environment |
| ISS | Flat fields |
| MAG | Support for MIMI, CAPS |
| MIMI | Measure shock accelerated ions and electrons |
| RPWS | Comprehensive measurement of plasma waves |
| UVIS | Airglow |
| VIMS | High resolution atmospheric sounding |
| *Earth* | |
| CAPS | Calibration |
| CDA | Characterize dust and meteor streams |
| ISS | Various calibrations, tests, and dark frames. Near UV lunar images for compositional studies. |
| MAG | Boom deployment 3 days before flyby. Alignment calibration. Calibration. |
| MIMI | Calibration |
| RPWS | Calibration |
| RSS | |
| UVIS | Lunar Calibration data |
| VIMS | Lunar Calibration data |
| RADAR | Signal reflection off of Earth's surface. Instrument verification and calibration. |

### 5.2. Venus Swingbys

Paradoxically *Cassini/Huygens* did not immediately head for the outer solar system but went inward toward Venus to pick up additional gravitational assistance because even the great thrust of the *Titan-Centaur* was insufficient to propel the massive spacecraft on its way to Saturn. Two Venus swingbys would be necessary followed by an Earth gravity assist plus one at Jupiter before the spacecraft had sufficient energy to climb far enough out of the Sun's gravitational potential well to reach Saturn. The purpose of observations made during Venus 1, Venus 2 and Earth swingby are shown in Table VII.

These flybys provided the *Cassini* Program with its first experience in designing coordinated scientific observations during a planetary encounter. These activities also exercised some of the scientific instruments as well as various operational capabilities of the spacecraft.

At the time of launch the plan was for the spacecraft to have very little activity until its approach to Saturn. Consequently, scientific observations were minimal during the first encounter of Venus that occurred on April 26, 1998, just six months after launch. Scientific data were obtained by the Radio and Plasma Wave Science instrument (RPWS) in a search for lightning (Gurnett *et al.*, 2001), and the Radio Science team (RSS) serendipitously captured the electron density profile of Venus' ionosphere while supporting telecommunications to Earth.

All of the sequence design had to be done by hand or with rudimentary software tools. The software for automation in spacecraft control and planning so necessary for the successful mission at Saturn did not exist at the time of launch. It was planned that development would be carried out over the years as *Cassini/Huygens* cruised to Saturn.

Many factors contributed to restrictions in the allowable spacecraft attitude for scientific observations during this early phase of the mission. The orientation of the spacecraft was constrained to keep the *Huygens* probe, aligned with the −X-axis, in the ecliptic and in the direction of the spacecraft velocity to provide a shield from micrometeoroids. The high-gain antenna (HGA) is aligned with the spacecraft −Z-axis and is usually pointed toward the Sun so as to shade the rest of the spacecraft. As long as the HGA remains Sun-pointed, any roll attitude about the Z-axis is allowable as long as it does not change the thermal characteristics of the spacecraft. Pitch maneuvers (about the X-axis) and yaw maneuvers (about the Y-axis) could be done to obtain a desired orientation, but might result in bringing thermally sensitive spacecraft components into sunlight. Thus, these maneuvers would require analysis of the thermal effects in order to assess whether or not they could be allowed. To further constrain spacecraft pointing, telecommunications during inner cruise were generally restricted to one of the two low gain antennas on the spacecraft (i.e., LGA-2) which is aligned with the −X-axis of the spacecraft. When LGA-2 is in communication with Earth, the allowable roll attitude is further restricted. In addition, sunlight, either direct or reflected from bright planets, must be kept out of the field of view of the two Stellar Reference Units (SRU) which provide the stellar navigation data used for attitude control. These are aligned with the +X-axis of the spacecraft. Radiators for the Visual and Infrared Mapping Spectrometer (VIMS) and Composite Infrared Spectrometer (CIRS) are aligned with the spacecraft x-axis and also have specified limits for their exposure to sunlight. All these constraints were accommodated when choosing the spacecraft attitude for the Venus-2 and Earth flybys.

The second swingby of Venus occurred at an altitude of 598 km at 20:30:07 UTC on June 24, 1999. The spacecraft approached from the dusk-side of the planet. The flyby provided a unique opportunity for the fields and particles instruments to study the interaction of the solar wind with Venus, a planet with no intrinsic magnetic field. *Cassini/Huygens* has a much more capable fields and particles payload than previous Venus missions. Since the flyby was at a low altitude, Venus' ionosphere could be reached. CAPS, MAG, MIMI and RPWS were powered on several hours before closest approach. The MIMI CHEMS sensor made measurements in the ionosheath and stagnation region at Venus and detected a number of energetic species, possibly pickup $O^+$ and $C^+$ ions. MIMI was able to detect energetic neutral atoms escaping from Venus' atmosphere with its ion and neutral camera (INCA). Plasma waves in the vicinity of Venus were measured over a broad frequency range and with increased sensitivity by RPWS. The high sampling rate allowed RPWS to again search for evidence of lightning, as they did during Venus-1. The magnetometer remained stowed in its canister because *Cassini/Huygens* was still too close to the Sun to expose its boom material to the heat of sunlight. During the Venus flyby the MAG was activated primarily to help identify boundaries such as the bow shock crossings in support of other instruments. Inbound and outbound bow shock crossings were nonetheless detected by significant jumps in magnetic field strength. The inbound bow shock crossing on the dusk flank was detected at approximately 19:20 UT and the outbound bow shock crossing at 20:40 UT, just 10 minutes after closest approach.

Several hours prior to the flyby at 14:40 UT the spacecraft performed a roll about the Z-axis of $-34.4$ degrees to allow the optical remote sensing instruments to view the planet. During the period around closest approach, the optical remote sensing instruments were pointed to the nadir. ISS, UVIS, and VIMS were sequenced to observe during the relatively short period (approximately 12 minutes) the planet was in their fields of view. Most of the ground track occurred over the night side of the planet where VIMS reported the first detection of thermal emission from the Venusian surface at 0.85 and 0.90 $\mu$m (Baines *et al.*, 2000).

A 20 mrad deadband was maintained through the Venus flybys[4]. For the Earth swing-by it was lowered to 2 mrad in order to accommodate the optical remote sensing observations of the Moon. Tracking passes on NASA's Deep Space Network of antennas (DSN) were scheduled at 1 per day on approach to Venus but increased to 3 passes per day to support the flyby. Nearly continuous DSN coverage was obtained during the Earth flyby.

### 5.3. EARTH SWING-BY

Four, planned, trajectory-correction maneuvers were executed in the fifty-four days between the Venus-2 and Earth flybys. The final corrections occurred seven days before reaching Earth. As a safety measure, the Earth-avoidance strategy had *Cassini/Huygens* aimed far away from Earth so that a collision with it was impossible. Consequently, as the range between the spacecraft and Earth decreased, it was necessary to successively increment the spacecraft path evermore inward, toward Earth, until, at last, it reached the correct swing-by distance to put it on the proper trajectory to Jupiter. The closest approach occurred at 03:28 UT on August 18, 1999 at an altitude of 1163 km over the southern Pacific Ocean.

In order to prepare for making observations, the VIMS IR-radiator and optics covers were jettisoned two days before closest approach. Shortly thereafter the 11-meter-long magnetometer boom was unlatched and allowed to deploy. Since launch the boom had been stowed in a cylindrical canister mounted along the Y-axis of the spacecraft. With the high gain antenna pointed toward the Sun, the entire canister was shaded. Deployment in the inner heliosphere (less than 0.97 AU from the Sun) was prohibited because the boom would become too warm and exceed its temperature tolerance. However, the magnetometers needed to be operational during the Earth swing by to obtain data in Earth's magnetosphere that would be critical for their calibration.

The magnetometer boom consists of inner and outer sections that deploy by what could be described as a telescoping action. The inboard section fully unfurls first and then the unfurling of the outboard section is initiated. The boom is springy and provides all of the force needed for its own deployment. It is unlatched and unfurls by itself. Viscous dissipation in a rate limiter keeps the boom segments from coming out too fast. The fluxgate magnetometer is mounted at the end of the inboard section and the helium magnetometer is mounted on the end of the outboard section. As anticipated, the boom deployed flawlessly on August 16, two days prior to the closest approach to Earth.

Earth's magnetosphere is the best-characterized space plasma and each of the fields and particles instruments was able to obtain data for the purpose of calibration as well as scientific investigation. Some of the instruments were turned on several days before Earth closest approach and thus also obtained data while the spacecraft was in the solar wind. The inbound bow shock signaling entry into Earth's magnetosphere was detected at 01:51 UT on August 18 at a distance of 15.1 $R_e$. Although the spacecraft orientation was not optimal for CAPS to obtain the best view of the plasma distributions to which they are sensitive, CAPS was able to identify all the magnetospheric boundaries from the inbound bowshock to the ionosphere. Boundary layer flows from the magnetopause, suprathermal plasma from the plasmasphere on the dayside, and ring current/plasma sheet structures were measured. MIMI's INCA sensor obtained energetic neutral atom images of Earth's ring current. Also, bursts of energetic magnetospheric ions from the long, dawn-sheath passage far downstream (58 to 392 $R_e$) of Earth were observed. RPWS successfully validated their wave-normal analysis capability by which they can determine the orientation of plasma wave fronts and polarization. They were also able to demonstrate the direction finding capability that was needed for their calibration at Jupiter in late 2000 to early 2001. In addition, *Cassini/Huygens*' rapid traversal enabled an excellent set of radio- and plasma-wave data that represents a 'snapshot' of the terrestrial magnetosphere. Once the boom was successfully deployed, the magnetometer team accomplished several calibration and scientific objectives. Earth's well-known magnetic field was used for calibration. The Science Calibration and Alignment Subsystem (SCAS), which produces a magnetic field vector in a direction that is accurately known, was operated several times to obtain information about the alignment of the magnetometer boom with respect to the spacecraft axes.

At 21:28 UTC, the day before the closest approach to Earth, the spacecraft was rolled 104.3 degrees about the z-axis. This allowed the Moon to traverse the fields of view of the ORS instruments. ISS, UVIS, and VIMS observed the Moon, which was at quarter phase, for as long as it was in their fields of view. For the WAC this was the longest, being about 29 minutes. Later, after Earth closest approach, the Moon was in the FOV of the VIMS solar port for approximately an hour and a half, allowing the acquisition of important calibration data.

After closest approach the flyby geometry was such that the high-gain antenna pointed at Earth. This allowed several minutes for the RADAR to transmit and receive a track of data that started over the southeastern Pacific Ocean and extended across South America. The main motivation for this measurement was to perform an end-to-end test using Earth as a target. These data allow the verification of instrumental parameters and calibration. This was the last opportunity for such testing before the first RADAR observations of Titan during the Saturnian tour.

The flyby took place during an interval when the solar wind was relatively fast, $\sim$600 km/s, and the interplanetary magnetic field had extended episodes of strong southward fields, up to 7 nT. Accordingly, Earth's magnetosphere was generally in a disturbed state during the encounter (Burton, *et al.*, 2001)[5].

*Cassini/Huygens* exited the magnetosphere on the dawn flank and returned to the solar wind at 55–65 $R_e$. The fields and particles instruments including UVIS were able to collect data through opposition in mid-September. At this time the geometry permitted use of the high gain antenna while it continued to function as a Sun shield. Models of the distant geomagnetic tail predict that it is aberrated or deflected from the Sun-Earth line due to the motion of Earth about the Sun and upstream magnetic field and solar wind conditions (Bennett *et al.*, 1997). Using such a model, it was predicted that *Cassini/Huygens* could pass through Earth's distant tail. Suggestive but inconclusive signatures of the deep tail were seen up to 6000 Earth radii downstream in the particle LEMMS data. A post-Earth trajectory change maneuver was performed thirteen days after the swing-by to set *Cassini/Huygens* on its proper course to fly by Jupiter on December 30, 2000.

### 5.4. The Jovian Flyby

The flyby of Jupiter produced more than just a gravitational assist for the spacecraft. Operations during this encounter served as a dress rehearsal for operations to be carried out later at Saturn. During the Saturnian tour, flybys occur frequently and the operational procedures must work perfectly. The lessons learned by exercising the spacecraft and instruments at Jupiter will greatly improve performance at Saturn. The trajectory for the flyby is shown in Figure 17 and compared with

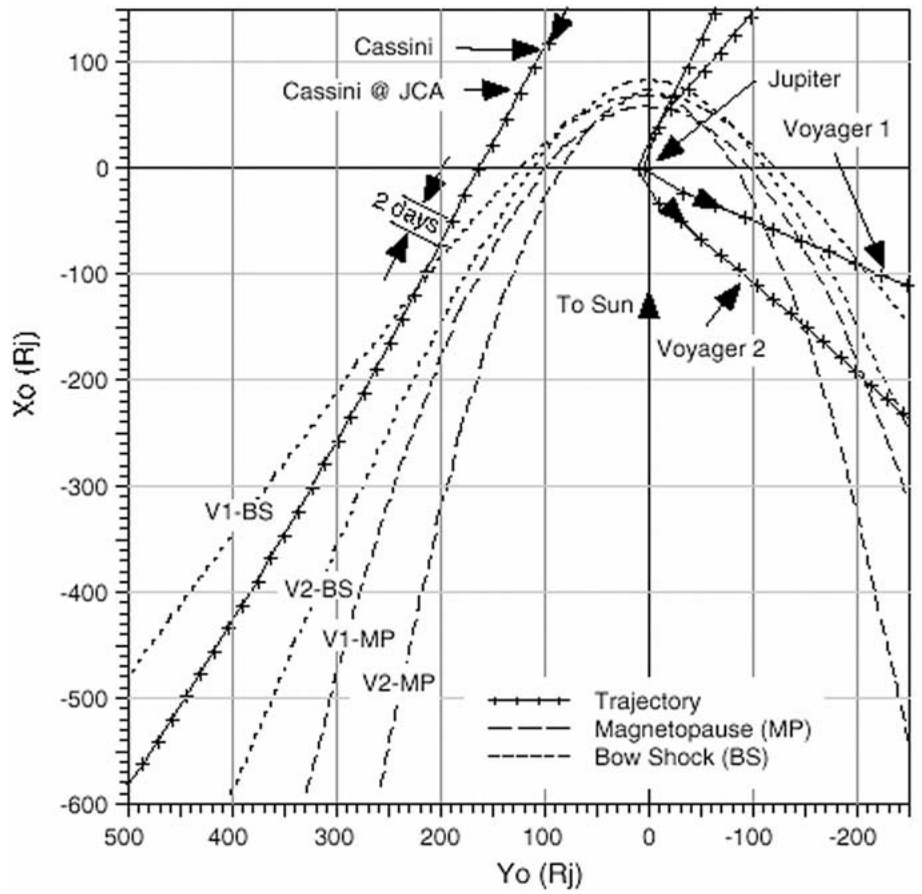


*Figure 17.* The path of the *Cassini/Huygens* Jupiter flyby compared with those of *Voyager 1* and *2*. Predictions are shown for the locations of the bow shock and magnetopause for different models.

predictions for the location of the bowshock and the magnetopause. In Figure 18 the trajectory of *Cassini/Huygens* is compared with the orbit of *Galileo.*

The *Cassini/Huygens* spacecraft flew by Jupiter on December 30, 2000, at a distance of 137 Jovian radii ($R_J \sim 71\,490$ km; altitude = 9 794 130 km), *en route* to Saturn for an arrival in 2004. Observations of Jupiter and the Jovian system spanned a six-month period, that began on October 1, 2000. Unique among the many scientific results of these observations are those which came from measurements conducted jointly using two spacecraft, *Cassini/Huygens* and *Galileo.* This is the first time that two spacecraft have been simultaneously near and inside the magnetosphere of a giant planet. Since December 1995, *Galileo* has been in orbit about Jupiter, carrying out scientific investigations. *Galileo* is a dual-spin spacecraft with a full complement of remote sensing and *in-situ* fields and particles instruments. Also, observations were coordinated with researchers using the Hubble Space Telescope (HST), Chandra the Very Large Array (VLA) of radio antennae,

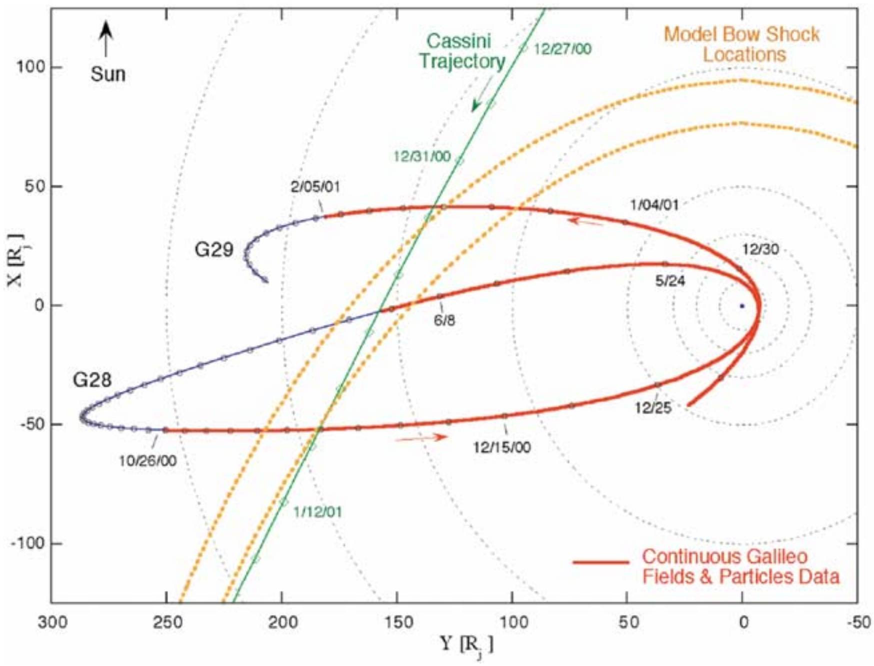


*Figure 18.* The locations of *Cassini* and *Galileo* during joint observing campaign. Tick marks on the *Cassini/Huygens* trajectory are daily positions whereas those for *Galileo* are for every fifth day. Other investigators used *Hubble*, *Chandra*, and Earth-orbital and ground-based instruments to observe the Jovian system at the same time. The campaigners were rewarded by a data set that is a discovery treasure trove.

the Deep Space Net (DSN), which is part of NASA's spacecraft communications system, and a number of ground-based astronomical observatories.

From *Galileo's* point of view, the collaborative work with *Cassini/Huygens* began on October 26th. For the next 100 days, *Galileo* collected data continuously as it moved from the solar wind, through the bow shock and magnetopause, into the middle and inner magnetosphere, and then back out through these regions and into the solar wind again. Approximately 60–70% of the data came down in real time and the remainder were recorded on tape. While some of the recorded data was returned to Earth in late December, the rest had to wait until the February to May 2001 when playback conditions were favorable.

Collaborations during the flyby period included a solar wind-Jupiter magnetosphere-aurora investigation involving *Cassini*, *Galileo* and the Hubble Space Telescope (HST), and a study of Jupiter's synchrotron emission involving the *Cassini* RADAR, the Very Large Array (VLA), the Deep Space Network (DSN), and the Goldstone Apple Valley Radio Telescope Project (GAVRT).

The extended approach and departure periods offered *Cassini's* optical remote sensing instruments (ORS) opportunities to carry out many observations. Unlike *Galileo*, *Cassini/Huygens* had an excellent communications link with Earth. The luxury of a very high data rate at the Jovian encounter allowed some detailed investigations of short-term variations or changes to be carried out. These include time-lapse movies of: (1) Jupiter's atmosphere (both inbound and outbound), (2) Io's torus, (3) Io in eclipse, and (4) the very faint Jovian rings. Other important observations included characterization of Io's dust stream(s), satellite spectral reflectance data, and Jupiter's synchrotron emission in a spectral range difficult to study from Earth. Below we briefly discuss some of the observations made at Jupiter. They serve to illustrate the richness of the observations we expect when the spacecraft reaches Saturn.

#### 5.4.1. *Magnetosphere*

The observations made by *Cassini/Huygens* are making important contributions to our knowledge of the Jovian magnetosphere. Some of these resulted from the unique advantage of the *Galileo* spacecraft being able to make similar measurements simultaneously. Other results were enabled by coordinated observations from Earth. These are discussed below, starting with *Cassini/Huygens'* measurements of the solar wind as it approached the Jovian magnetosphere.

A primary goal was to compare a solar-wind-dominated magnetosphere (e.g., Earth), and a magnetosphere dominated by rotation (e.g., Jupiter), to Saturn, for which both the solar wind and rotation are likely to be important magnetospheric drivers. Inbound *Cassini* measured the solar wind while *Galileo* measured deep in the magnetosphere. Outbound, the roles became reversed with *Galileo* measuring the solar wind while *Cassini* was in and out of the magnetosphere many times as it traveled along the dusk flank. The simultaneous measurements of the solar wind and magnetosphere allowed variations in the magnetosphere to be correlated with changes in the interplanetary environment. Although numerous reconfigurations and substorm-like activities were observed by *Galileo* prior to *Cassini/Huygens's* flyby, there had been no way to associate these events as a response to changing conditions in the solar wind impinging upon the magnetosphere.

*Cassini/Huygens* was the first spacecraft to explore the dusk flank of the Jovian magnetosphere. Of special interest were the processes of magnetic field draping (measurements by MAG), flow dynamics (measurements by CAPS), detached-plasma shedding (measurements by CAPS, and MAG), the generation of upstream waves (measurements by RPWS), and the shaping of the overall magnetic topology (measurements by MIMI, CAPS, and MAG). *Cassini/Huygens*, flight trajectory and fluctuations in solar wind pressure and rotation of the Jovian magnetic field caused the spacecraft to cross the bow shock and the magnetopause repeatedly. In all, there were 44 bow shock crossings and 6 crossings of the magnetopause! The locations and dynamics of these boundaries are important for an overall understanding of Jovian magnetospheric dynamics and they place significant constraints on magnetospheric models.

CAPS sensitivity and mass resolution permitted the first detailed compositional analysis of Jupiter's thermal magnetospheric plasma in the outer regions of the magnetosphere. CAPS can easily resolve ion species associated with oxygen, sulfur, potassium and related molecules such as $S_2^+$ and $SO_2^+$. CAPS and MIMI can also distinguish between singly charged and multiply charged ions and thus establish the ratio of the two. This information helps to constrain the location and strength of sources, transport processes, and the mechanisms by which the middle and inner regions of the magnetosphere are populated with hot plasmas. RPWS monitored Jovian radio emissions and plasma-and radio-wave phenomena associated with the Jovian bow shock, dusk magnetosheath and possibly from the dusk magnetopause and magnetosphere. It remotely sounded the structure of the Io torus by using measurements of Faraday rotation and observations of the location and frequency of the narrow-band kilometric radiation. Multipoint observations by *Cassini/Huygens* and *Galileo* have provided the data for a better understanding of the beaming properties of Jovian radio emissions.

Cassini's MIMI instrument includes an energetic neutral atom camera (INCA). Energetic neutral atoms typically arise from charge exchange interactions between a neutral atom and an energetic ion trapped in the magnetic field. Upon charge exchange the ion is neutralized and is no longer bound by the magnetic field. It leaves the site of the reaction at high speed. Imaging these neutrals permits the direct observation of the charge exchange reactions. This allows some inferences of the spatial, energy, and mass distributions of the trapped ion populations. MIMI also provided *in situ* measurements of the more energetic species encountered by the spacecraft. These complement measurements by CAPS over a large range of energy (up to 130 MeV). *Cassini* coordinated observations with the Very Large Array (VLA) radio telescope and took advantage of the flyby to map Jupiter's synchrotron radiation. *Cassini's* RADAR operated as a radiometer at a wavelength of 2 cm while the VLA mapped emission at wavelengths of 20 and 90 cm. This provided comparative measurements of the relativistic electron population in Jupiter's radiation belts and enabled the most nearly complete estimate of their energy spectrum (up to 50 MeV) and density of the electrons in the radiation belts made to date. Observations of synchrotron emission provide the only remote probe of high-energy electrons in Jupiter's inner radiation belts.

Jupiter's aurora has been observed to vary on short time scales, from minutes to days. This variability is thought to be due to the combined influence of internal magnetospheric processes and external, solar-wind-driven changes. Unlike terrestrial aurora that are solar-wind-driven, Jupiter's auroral morphology shows dependencies on both the solar wind and Jupiter's rotation. The HST (Hubble Space Telescope) carried out coordinated observations in order to correlate changes in the intensity and morphology of Jupiter's aurora with the state of the solar wind as measured by Cassini. Inbound to Jupiter, *Cassini* monitored the solar wind while *Galileo* measured magnetospheric properties and HST imaged the aurora. Outbound, *Cassini* monitored the nightside aurora while *Galileo* monitored the solar wind and HST observed the dayside aurora. This data set permits solar wind influence on auroral intensity and structure to be separated from changes due to internal magnetospheric processes.

### 5.4.2. *Atmospheric Structure and Dynamics*

Atmospheric observations of Jupiter studied atmospheric kinematics and meteorology over time scales ranging from hours to months, measured wind velocities and life cycles of atmospheric features, and monitored interactions of storms and jets. These data will improve our knowledge of the 3-dimensional structure of the atmosphere and the global energy balance. Information was obtained on the distribution of oxygen compounds and higher order-hydrocarbons. CIRS searched for new spectral features and globally mapped the thermal structure and aerosol loading of the stratosphere, as well as obtaining some information on temporal variability. Wind shear and eddy signatures in the thermal field give information on the attenuation or propagation of tropospheric kinematics into the stratosphere. *Cassini/Huygens* helped to establish a link between daytime storm features and moist convection, as evidenced by lightning, at night. Adequate lightning statistics were gathered to link moist convection to cyclonic shear zones. Jovian dayglow and nightglow emissions were also measured.

Inbound, a 'Zoom Movie' was built up by acquiring Optical Remote Sensing (ORS) (i.e., CIRS, ISS, UVIS, and VIMS) data for all odd rotations of Jupiter from $-90$ to $-20$ days, plus one even rotation every 120 hours. ISS and VIMS imaged every 60° of longitude while data was acquired more or less continuously by CIRS and UVIS.

The inbound sequences were interrupted when scientific operations were suspended in order to investigate an out-of-specification signal from the Attitude Control System. It was found that one of the spacecraft's reaction wheels required more torque at very low rpm than expected. This problem was resolved by changing the operating range for the wheels so that low rpm rotation rates would be avoided.

Outbound, a zoom movie was acquired from $+20$ to $+90$ days, for all odd rotations of Jupiter, plus one even rotation every 120 h. Both the bright crescent and the dark hemisphere were observed.

Observations of Jupiter's atmospheric thermal emission and synchrotron emission were obtained shortly after Jupiter closest approach ($\sim$137 $R_J$ distant from Jupiter). Two cm wavelength maps were obtained by using RADAR operated in its radiometer mode and slewing the spacecraft repeatedly across the emission region ($\sim$8 $R_J$ in width). Two 10-hour maps covering all Jovian longitudes were obtained (one for each polarization). The resolution of the maps is approximately 0.25 $R_J$ (Bolton, *et al.*, 2002).

### 5.4.3. *Jovian Rings*

The Jovian ring is very faint and difficult to observe due to its proximity to the planet. *Cassini/Huygens'* objectives were to investigate the interaction between Jupiter's small satellites and its ring to assess the sources and sinks of ring material. A joint experiment was carried out with *Galileo* to characterize the three-dimensional structure of the rings by imaging them at the same time from two different perspectives. A watch was maintained for any temporal variability. Two ring 'movies' were taken, the first inbound at $-18$ days with a duration of 40 h, and the other outbound at $+16$ days, for 39 h. The solar phase angle reached $\sim$0 deg during the inbound movie, which allowed observations of the 'opposition effect', a backscattering effect closely related to the values of certain photometric parameters. Although *Cassini's* spatial resolution could not compete with that of *Galileo*, the spectral range, available phase angles, and temporal coverage offered the opportunity to acquire valuable data, complementary to that obtained by *Galileo.*

5.4.4. *Galilean Satellites and Himalia*

*Cassini/Huygens* was blessed by an opportunity to obtain data on Himalia, a small satellite that heretofore had escaped observations by *Galileo* due to the lack of a favorable opportunity. Himalia was observed at a range of $4.4 \times 10^6$ km for a duration of $\sim$3 h. VIMS obtained the first visible to near-IR reflection spectrum of Himalia (Brown *et al.*, 2002). The purpose of this observation was to determine surface composition. ISS obtained some images that are useful for assessing Himalia's rotation rate and size ($\sim$160 km diameter).

The timeline featured relatively dense coverage for Io and Europa, and relatively sparse coverage for Ganymede and Callisto. However, *Cassini* was able to observe both Europa and Callisto at near 0° phase angle and measure the surge of their opposition effects.

A search was carried out for new infrared spectral features. VIMS has nearly double the spectral resolution of *Galileo's* NIMS and obtained spectra of the Galilean satellites in order to improve the determinations of their surface compositions, particularly the compositions of the non-icy components. It has been suggested that this component is rich in hydrated salts (i.e., magnesium and sodium sulfates) and they may be a signature left by water that came to the surface from an ocean below (McCord, *et al.*, 2001).

In the visual, ISS acquired phase angle and polarization data to improve knowledge of the phase function and thereby physical characteristics of the surface such as grain size and packing. ISS also observed Io while it was in Jupiter's shadow in order to examine the morphology and temporal variability of eruptive plumes, atmospheric airglow, and volcanic hot spots. At this time a very impressive set of images was obtained enabling a movie that shows changes in optical emission that come from changing interactions between the magnetosphere and Io's very thin exosphere.

5.4.5. *Io's Torus*

Closely related to Io's exosphere are the two tori that are centered on Jupiter. One is composed of neutral atomic and molecular species and the other is composed of ions. They orbit at Io's distance from Jupiter and are thought to originate from

Io. Measurements of the emissions from these species are used to study the sources and sinks of material, its composition, its dynamical behavior, and its dependencies on local time, Io's phase, Jovian longitude and Io's degree of volcanic activity. In a 5-day period, 70 h was spent monitoring Io's torus and UVIS collected enough data to produce a torus movie showing stimulated emission from some ion species.

#### 5.4.6. *Dust*

To measure the general dust populations, CDA remained on for most of the Jovian flyby, as well as the months and years during cruise. In 1992 *Ulysses* discovered collimated dust streams coming from Jupiter. Later observations with *Galileo* showed that Io was the source. Jupiter's magnetospheric plasma charges dust particles coming from Io. These are then accelerated by Jupiter's corotational magnetic field.

*Cassini's* CDA is the most capable dust instrument that has observed these particles. CDA can measure their flux ($\sim$1 per month to $\sim 10^4$ s$^{-1}$), mass ($\sim 10^{-16}$ to $\sim 10^{-6}$ gm; $\sim$0.1 to $\sim$10 μm diameter for common silicates), velocity (1–100 km s$^{-1}$), charge ($\sim 3 \times 10^{-1}$ to $\sim 3 \times 10^{-12}$ Coulomb), and composition (resolving power of $\sim$70 M/dM). The measurement of the chemical composition of the dust is a new capability that CDA brings to this problem, and it may yield further insight into Io's volcanic activity. Coordinated measurements were made by *Cassini* and *Galileo* to separate temporal and spatial effects discernible in the structure of the dust stream by using data from two spacecraft. This coordinated experiment is illustrated in Figure 19. Much to the surprise of everyone, velocities turned out to be in the 300–400 km/sec range (Srama, *et al.*, 2001). Mechanisms to attain such high dust velocities are being studied.

### 5.5. Gravitational Wave and General Relativity Radio Experiments

On its voyage between Jupiter and Saturn, *Cassini/Huygens* will carry out gravitational wave searches during the three successive oppositions of the spacecraft, beginning in December 2001. These are Doppler-tracking, radio experiments that involve two-way Ka-band tracking of the spacecraft by the Deep Space Network (DSN). Propagating, polarized gravitational fields are predicted by all theories of relativistic gravity. These waves change the distance between separated (known) masses and shift rates at which separated clocks keep time. Compared to electromagnetic waves, gravitational waves are extremely weak. Detectable amplitudes of these waves are only generated by astrophysical sources. In the *Cassini/Huygens* experiments the distances between the spacecraft and Earth are large compared to the wavelength. Because of this, there will be, in general, three distinctive components to the gravitational wave signature (in a relative-Doppler versus time plot). This experiment is sensitive to low frequency gravitational waves (0.1 to $10^{-4}$ Hz). Observations during the first opposition (December 2001–January 2002) went well.

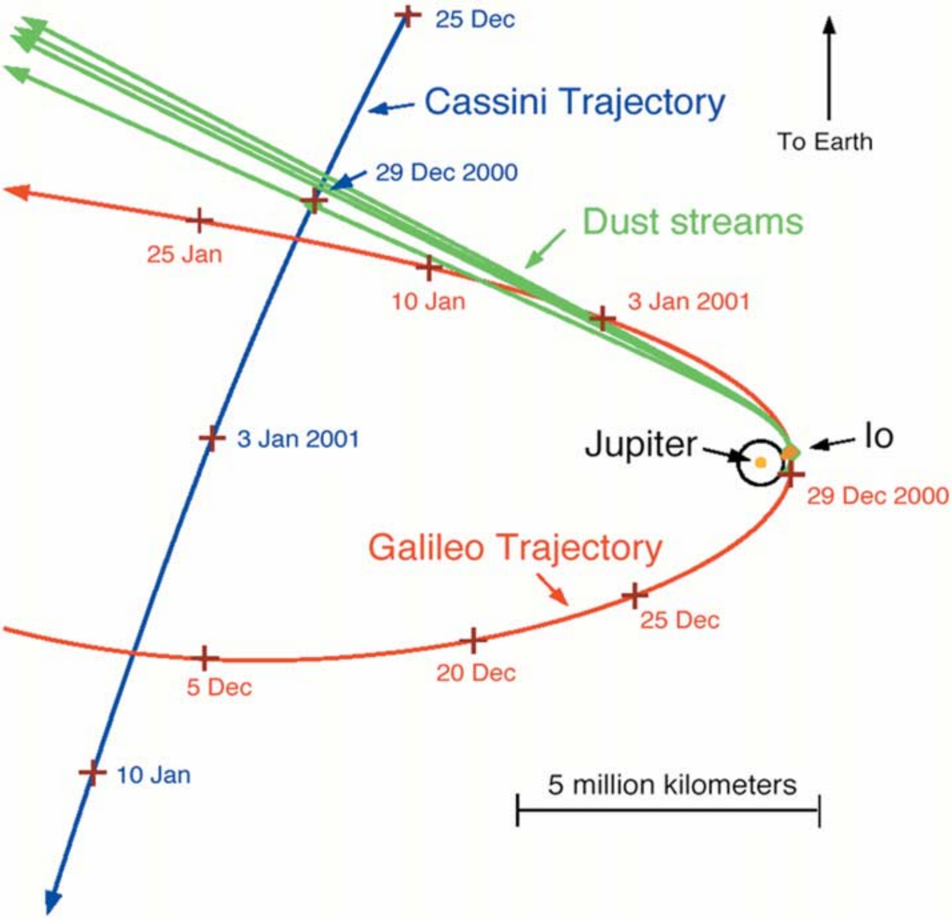


*Figure 19.* The configuration for the two spacecraft dust experiment. The radiants of dust stream from Io and intersect the trajectories of *Galileo,* first, and then *Cassini/Huygens.* The time it takes the dust to fly between the spacecraft can be measured by observing the temporal modulation of the density of the stream. Particle velocities turned out to be hundreds of kilometers per second, a value much higher than thought to be possible.

The fractional frequency stability (e.g., Allan variance) of the radio system has been measured and was better than its manufactured specification.

During two conjunctions of the spacecraft with the Sun, a series of radio propagation measurements will be made using two-way X-band and Ka-band DSN tracking. These will provide the basis for a test of general relativity, as well as obtain data on conditions in the solar corona.

## 6. The Cassini/Huygens Mission at Saturn

The *Cassini/Huygens* mission has three main phases at Saturn: arrival and insertion into orbit, the *Huygens* mission, and the orbital tour. Each of these will now be discussed.

### 6.1. Arrival at Saturn and Insertion into Orbit

Months before reaching Saturn, *Cassini* begins making synoptic observations in order to refine our knowledge of Titan and to characterize the rings and the planet as early in the mission as possible. As soon as a few tens of pixels are available across Saturn's disk the first characterization of the atmosphere with Cassini's instruments can be started. This early work will establish the first point in Cassini's kinematic coverage. It will also obtain the information we need for all targets in order to refine our knowledge of (remote sensing) instrumental sensitivities as a function of wavelength and other parameters. As the range to Saturn continues to decrease it will be opportune to make a movie showing the kinematics of the atmosphere.

Phoebe, the target of our first flyby in the Saturnian system, is reached on 11 June 2004. At this time the range to Saturn is still some 11.3 million kilometers. Phoebe has a modest diameter of 150 km. It has a rotation period of about 9.4 h and an orbital period of 550 days. Phoebe is unusual because of its inclined, retrograde, and chaotic orbit. This is strong evidence that it and a dozen recently discovered small satellites were interplanetary objects that have been captured perhaps from the Kuiper-belt. Measuring the density of Phoebe is key to assessing its bulk composition. There is some evidence from albedo measurements that there may be craters on the surface of Phoebe. This flyby is *Cassini*'s only encounter with Phoebe because this satellite is so distant from Saturn that *Cassini* cannot afford to expend the propellant needed to visit it again, later in the mission. The flyby of Phoebe occurs 19 days before SOI and the corresponding Sun-Earth-spacecraft angle is six degrees. The Phoebe distance at closest approach will be 2000 km and the phase angle will be less than 90°.

The trajectory of the spacecraft as it approaches the rings and planet is shown in Figure 20. The spacecraft is beneath the E ring from about 4.5 h to 2.75 h before periapsis. The spacecraft passes through the gap between the F and G rings at 1.86 hours before periapsis and again at 1.90 h after periapsis in the descending direction. During this arrival trajectory, the spacecraft will be at its closest to Saturn and the inner rings. The closest approach is 0.3 $R_s$ (1 $R_s$ = 60 330 km); the next closest is 1.7 $R_s$ which occurs at several times late in the tour. Consequently, the initial pass of Saturn is a unique opportunity for making key observations.

Figure 20 shows the arrival trajectory from a view point above Saturn. Note that the trajectory just grazes the solar and Earth occultation zone behind the planet. This means the spacecraft will be in sunlight for the entire SOI sub-phase. The Earth occultation zone is not significant because the spacecraft will have turned

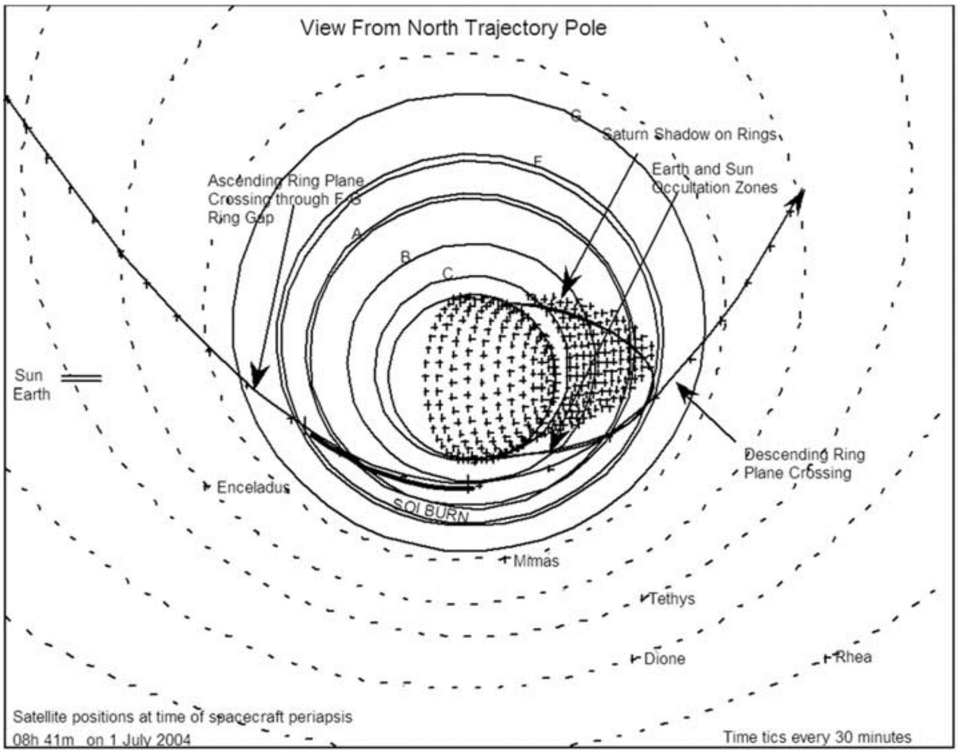


*Figure 20.* Saturn Orbit Insertion (SOI) geometric relationships. The view is from above Saturn's north pole. After launching from Earth, the placing of *Cassini/Huygens* into orbit is the most important event. The proximity to the planet and the rings makes this a uniquely valuable period for scientific measurements.

off of the Earth-line before the first ring plane crossing. The SOI burn begins soon after the ascending crossing and ends at approximately Saturn closest approach. The maneuvers before SOI are planned to insure the proper spacecraft trajectory for the orbit insertion maneuver. Maneuvers after SOI are to correct for errors in the insertion burn itself. The B-plane delivery error at the orbit insertion point is expected to be less than 130 km (one sigma). The SOI maneuver itself occurs on 1 July 2004, and is timed so that a normal burn will end just after closest approach.

*Cassini/Huygens* will be the fourth spacecraft to pass through the rings of Saturn. A region known to be free of particles has been chosen. Any debris to be encountered during the ring plane crossings is expected to be of small size and very low mass (e.g., smoke) which the spacecraft has been designed to withstand. The orbit insertion burn slows the spacecraft and allows it to be captured into orbit about Saturn. The SOI burn will occur earlier in time (than optimum for minimizing propellant usage) so that the burn will end near the closest approach to Saturn. This allows time for post-periapsis remote sensing of the rings. Otherwise, should the burn fail to execute as planned, this time will be used to fire the second engine and complete the maneuver to attain Saturnian orbit.

The SOI maneuver itself is a 97-minute main engine burn with a total $\Delta$V of 633 m/s. An accelerometer will end the burn when the required velocity change has been obtained. The spacecraft will be steered at approximately a constant angular rate with the engine gimble actuator to keep the main engine pointed near the velocity vector in order to maximize the thrust efficiency during the burn. Thus the spacecraft will turn approximately 40° in all during the burn.

During the SOI burn itself, only fields, particles, and wave instruments will be operational. It is necessary to keep high power margins for the critical burn event; also, the fixed pointing and spacecraft vibrations during the main engine firing would degrade remote sensing. After the burn has ended and the sloshing in the fuel tanks has subsided ($<$5 minutes), the spacecraft will be rolled 60–70° to allow the ORS instruments to view the Saturn inner rings that are not in shadow. The ORS viewing angle is 20–30° from nadir. This look-angle is a compromise between the desires of the MAG investigation and the ORS instrument investigations. At this time *Cassini/Huygens* is the closest to Saturn and this is also the only time that this portion of the planet's magnetic field will be available for measurement. It is also the best time to view the rings up close.

### 6.2. Huygens Probe Mission

The first two orbits about Saturn are used to set up the necessary trajectory for deploying the *Huygens Probe* on the third orbit. On December 16, 2004, three days after the end of the second orbit, the Probe Targeting Maneuver places *Cassini/Huygens* on a course that will intersect Titan. The *Orbiter* then turns to aim *Huygens* at Titan. On December 25th the *Probe* is released. The spin-eject mechanism simultaneously ejects the *Probe* and imparts to it a 5 rpm axial spin. The two spacecraft separate with a relative velocity of 0.3 to 0.4 m/s. Twenty-two days later, January 14, 2005, *Huygens* will reach Titan. Meanwhile, the *Orbiter* fires an engine and executes the *Orbiter* Deflection Maneuver. This sets a course to fly by Titan at an altitude of 60 000 km and at the right time for receiving transmissions from *Huygens.*

The general situation for this part of the mission is depicted in Figures 21 and 22. The spin-stabilized *Probe* is targeted to enter Titan's atmosphere at latitude $-10.7°$ and 199° *west* longitude. Winds during the descent will determine the exact landing location. Windage is expected to be almost entirely in longitude. Depending upon the direction and intensity of the wind, the position of the landing could differ from the above longitude by plus or minus half a dozen degrees or so.

The *Orbiter* is turned to point and track the HGA on the expected *Probe* entry point. The *Probe* support avionics (PSA) are configured to receive data. *Orbiter* instruments will be turned off. *Huygens* enters the atmosphere 2.1 h before the *Orbiter* will reach its closest approach to Titan[6]. The *Probe* has a thermal-protection

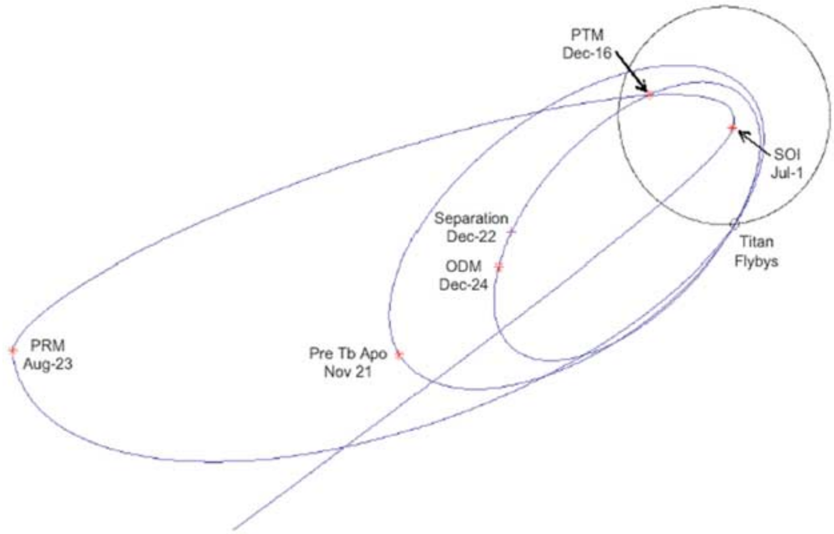


*Figure 21.* Events and trajectories leading up to the delivery of *Huygens.* Three orbits are needed to set *Cassini* on the correct trajectory so that it can meet *Huygens* exacting requirements for entering Titan's atmosphere. PRM is the periapse raise maneuver; PTM is periapse trim maneuver; ODM is the *Orbiter* deflection maneuver that keeps the *Orbiter* from following *Huygens* into Titan.

shell to protect it from the enormous flux of heat generated during atmospheric entry. Atmospheric entry is a tricky affair. Entry at too shallow an angle can cause the *Probe* to skip out of the atmosphere and be lost, whereas too steep of an angle will result in it being burned up in the atmosphere. The designed flight path entry angle is ~64 degrees. Once the *Probe* has decelerated to about Mach 1.5, the aft cover is pulled off by a pilot parachute. An 8.3-m diameter main parachute is then deployed to initiate a slow and stable descent. The main parachute slows the *Probe*, allowing the decelerator/heat shield to fall away as it is released. To limit the duration of the descent to a maximum of 2.5 h, the main parachute is jettisoned at entry +900 s and a smaller, 3.0 m diameter, drogue chute is deployed for the remainder of the descent. The entry and descent sequence is illustrated in Figure 23, which shows the major events of *Huygens'* mission. The batteries, and all other resources, are designed for a maximum mission duration of at least 153 min. This corresponds to a descent time of 2.5 h plus 3 min.

The *Probe* measures atmospheric properties *in situ* as it descends by parachute to the surface. Throughout the descent, the HASI (*Huygens* Atmospheric Structure Instrument) will measure more than a half dozen physical properties of the atmosphere. It will also process signals from the *Probe*'s radar altimeter in order to gain information about surface properties. The Gas Chromatograph and Mass Spectrometer (GCMS) will determine the chemical composition of the atmosphere as a function of altitude. The Aerosol Collector and Pyrolyzer (ACP) will capture aerosol particles, pyrolyze them, and send the effused gas to the GCMS for analysis.

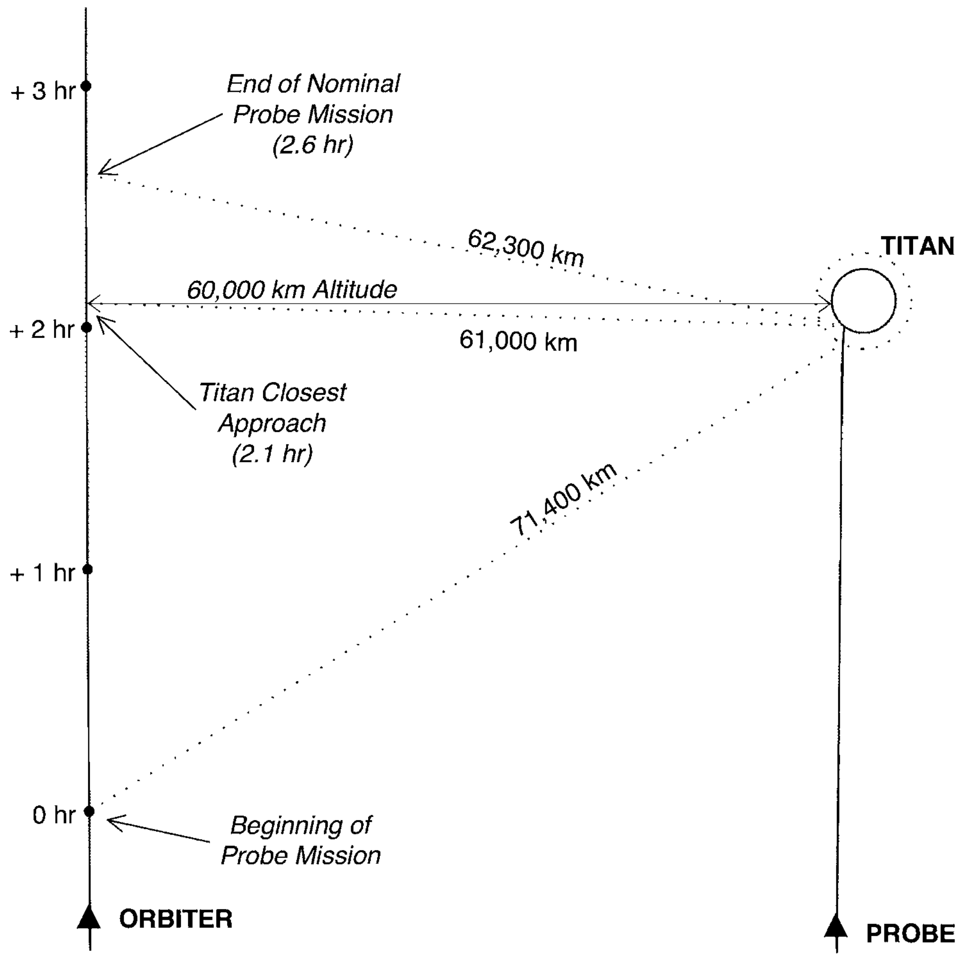


*Figure 22.* Relative positions of the *Probe* and *Orbiter* during *Huygens'* mission. (PAA = probe aspect angle; ODT = *Orbiter* delay time; HGA = high-gain antenna).

The Descent Imager and Spectral Radiometer (DISR) will measure the propagation of sunlight in the atmosphere. This instrument will also image the cloud formations and the surface. As the surface nears, the DISR will switch on a bright lamp and measure the spectral reflectance of the surface. Throughout *Huygens*' descent, the Doppler shift of telemetric signal will be measured by equipment on the *Orbiter* in order to determine the atmospheric winds, gusts, and turbulence (the Doppler Wind Experiment, DWE). In the proximity of the surface, the Surface Science Package (SSP) is active. Its accelerometer characterizes the impact of touchdown. In the atmosphere SSP measures the local velocity of sound, electrical permittivity, temperature, and thermal conductivity. If the landing is into a liquid, SSP will measure density, velocity of sound, and index of refraction.

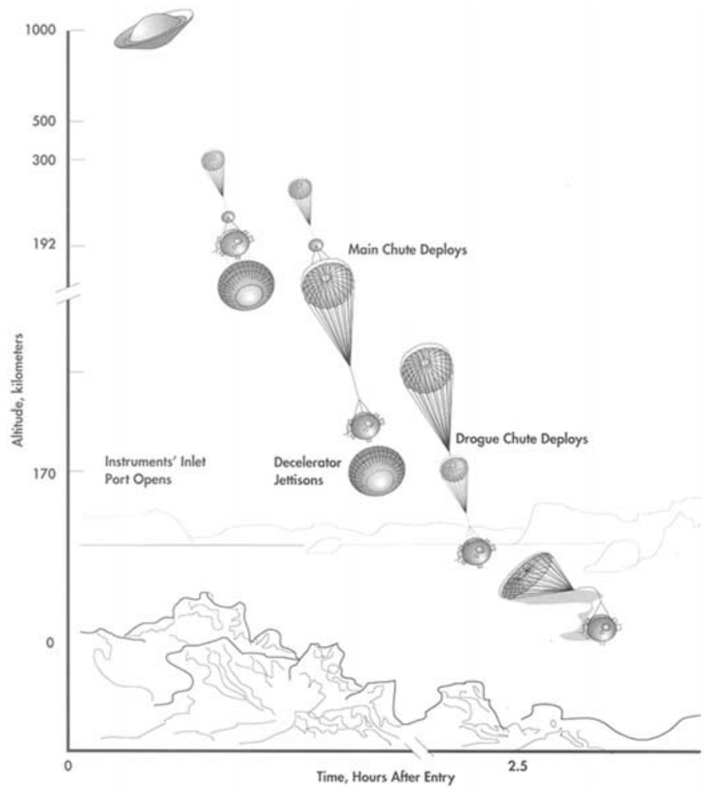


*Figure 23.* A schematic representation of major events during *Huygens'* mission.

The data are transmitted in two separate streams, and both are recorded redundantly on each SSR. In all, there are four copies, not counting any duplication between the two *Huygens* communication channels. The maximum length for the expected descent time is 2.5 h. At this time the Orbiter is slightly pass closest approach (first tick mark in Figure 22) and *Huygens* will be on the surface. For about two hours the *Orbiter* will listen for transmissions from the surface. At ~2.4 h after periapsis the *Orbiter*, as seen from the *Probe,* will pass over the horizon. Soon thereafter, the *Orbiter* will turn the high-gain antenna towards Earth and begin transmitting the recorded data. The complete, 4-fold redundant set of *Probe* data will be transmitted twice. Verification of receipt of the data on the ground will be made independently by JPL and ESOC.

### 6.3. THE ORBITAL TOUR

After the delivery of *Huygens*, *Cassini* is put on orbits that take it to the icy satellites, explore much of the volume of the magnetosphere, and to high latitudes to observe the rings. *Cassini* uses close flybys of Titan both to study Titan and

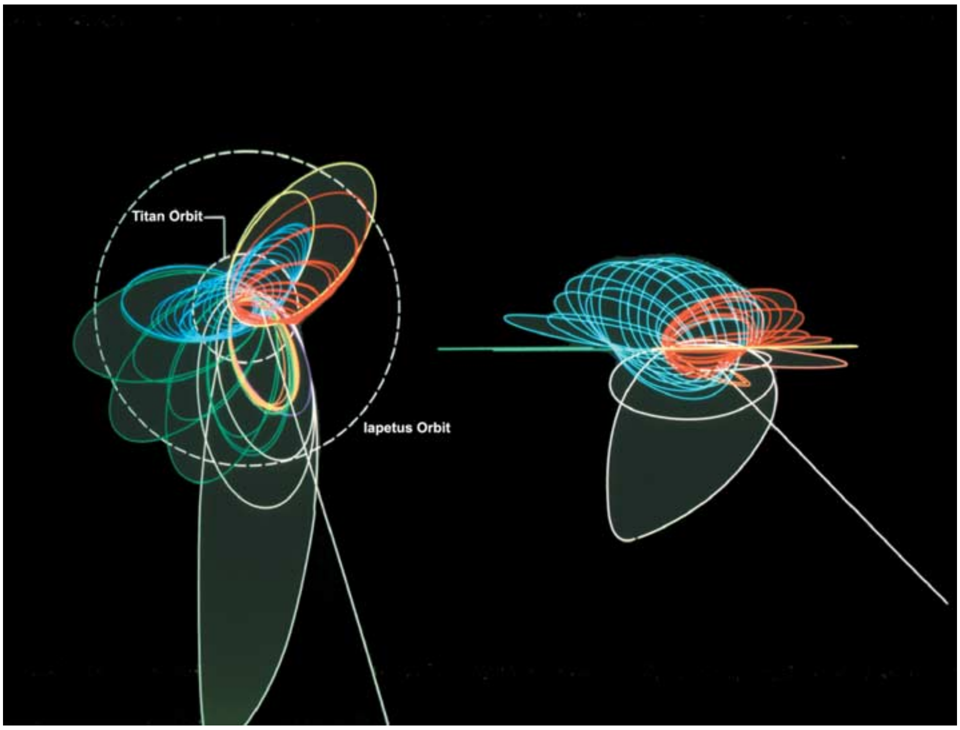


*Figure 24.* The orbits for the tour of the Saturnian system. On the left the view is from above Saturn's north pole. On the right the observer is in the planet's equatorial plane with the sun to the right. The dashed orbits of Titan and Iapetus provide the scale. Colors identify different classes of orbits.

to obtain gravitationally assisted orbit changes. These maneuvers will permit the achievement of orbits with a wide range of desirable characteristics.

The tour consists of 76 Saturn-centered orbits. They are navigated by using propulsive maneuvers and 45 Titan-gravity-assist flybys. The size of these orbits, their orientation to the Sun-Saturn line, and their inclination to Saturn's equator are gauged to assist in meeting the scientific requirements. These include: Titan ground-track coverage, targeted flybys of icy satellites, Saturn, Titan, and ring occultations, maximum orbit inclination, and ring-plane crossings. Titan is the only satellite that is large enough to provide significant gravity-assisted orbit changes. The design of the *Cassini* orbital tour was a complicated and challenging activity. It is a very aggressive tour compared to that in the *Cassini* AO. Its success in yielding many opportunities, in part, helps to compensate for the handicap that was introduced early in 1992 when the instrument platforms were deleted from the spacecraft design as a cost-saving measure.

The tour is shown in Figure 24. The outer dotted circle corresponds to the orbit of Iapetus. The various segments of the tour are color-coded. White indicates the period of 2004 July 1 to 2005 February 15 and includes SOI, the *Probe* release, and *Huygens* mission. Violet is 2005 February 15 to 2005 April 1. Orange is from

2005 April 01 to 2005 September 7 and includes a series of important occultation sequences. Green is 2005 September 7 to 2006 July 22 and gives the petal rotation and magnetotail petal. Blue goes from 2006 July 22 to 2007 June 30 and includes a 180-degree transfer. Yellow is 2007 June 30 to 2007 August 31 and includes apoapsis rotation in order to get certain icy satellites flybys. Red goes from 2007 August 31 until the end of mission (2008 July 1) and is chiefly the high inclination sequences[7].

In addition to the deliberately targeted flybys, there are unplanned or serendipitous flybys that occur as a result of the tour geometry. Many of these are close enough to provide valuable opportunities for observations. On these occasions, ranges can be less than 100 000 km. At that range the pixel resolution of *Cassini*'s narrow-angle camera is about 0.6 km. This is substantially better than that achieved by *Voyager* for most of the icy satellites. Wolf (2002) will revisit mission and tour design in more detail in a later volume.

## 7. Data return and Distribution to the Scientific Community

What will we do with all of the data that *Cassini/Huygens* will collect? Upon the first inspection they are checked to see if the downlinks were successful and if the respective instruments appear to be functioning correctly. The instrument teams peruse the data for obvious surprises. Some of these may be new discoveries. If they are newsworthy they go onto a fast track for release to the world. Meanwhile, the data also go to the respective scientific teams and investigators. These are the people who are responsible for the initial analysis and study of the data. They render the results into forms appropriate for publication in the scientific literature. However, because of the continuing spacecraft operational chores and because of the very large amount of data that *Cassini* will return, they can only scratch the surface in terms of developing the scientific results in the data. One year after receipt of the data by the Cassini scientific teams, the data become available to everyone via NASA's Planetary Data System. At this time the whole worldwide community of scientists has the data available for its use and everyone is able to participate in the further exploitation of the data. But, in reality, the challenge of interpreting all that has been measured, photographed, and returned has just begun. The further analysis of these data over the years to come will be the continuing legacy of the *Cassini* and *Huygens* missions.

## Notes

1. As of summer 2001, observations suggest the presence of additional satellites but their orbits are presently unknown. Undoubtedly there are many additional small, as yet undetected, satellites.
2. The membership of the Joint Science Working Group which supported the phase-A activities as follows: M. Allison (Goddard Institute for Space Studies, New York, USA); S. Bauer

(Karl Franzens Universitat, Graz, Austria); M. Blanc (Centre de Recherches en Physique de I'Environnement, St. Maur, France); S. Calcutt (Dept. of Atmospheric Physics, Oxford, UK); J. Cuzzi (NASA Ames Research Center, Moffett Field, USA); M. Fulchignoni (Universita 'La Sapienza', Rome, Italy); D. Gautier (Observatoire de Paris, Meudon, France); D. Hunten (University of Arizona, Tucson, USA); W. Ip (MPI für Aeronomie, Katlenburg-Lindau, Germany); T. Johnson (Jet Propulsion Laboratory, Pasadena, USA); H. Masursky (US Geological Survey, Flagstaff, USA); P. Nicholson (Cornell University, Ithaca, USA); T. Owen (State University of New York, Stony Brook, USA); R. Samuelson (NASA Goddard Space Flight Center, Greenbelt, USA); F. Scarf (TRW, Redondo Beach, USA); E. Sittler (NASA Goddard Space Flight Center, Greenbelt,USA); B. Swenson (NASA Ames Research Center, Moffet Field, USA);. D. Gautier, W. Ip and T. Owen acted as 'lead scientists'.

3. The National Aeronautics and Space Administration (NASA) in the United States and the European Space Agency (ESA) in Europe. Support to the study was provided by: M. Bird (Univ. of Bonn, Germany); R. Courtin (Observatoire de Paris, Meudon, France); E. Grün (MPI für Kernphysik, Heidelberg, Germany), M. Flasar (NASA/GSFC, Greenbelt, Maryland, USA); G. Israel (Service d'Aeronomie, Verrieres-le-Buisson, France); V. Kunde (NASA/GSFC, Greenbelt, Maryland, USA); E. Lellouch (Observatoire de Paris, Meudon, France); S. Madsen (TU of Denmark, Lyngby, Denmark); D. Muhleman (Caltech, Pasadena, California, USA); H. Niemann (NASA/GSFC, Greenbelt, Maryland, USA); G. Orton (Jet Propulsion Laboratory, Pasadena, California, USA); F. Raulin (LPCE, Creteil, France); M. Tomasko (University of Arizona, Tucson, Arizona, USA). The ESA members from the Scientific Directorate responsible for the phase-A study were: G. Haskell (Science Planning Office, ESA HQ, Paris), M. Coradini (Science Planning Office, ESA HQ, Paris), J.-P. Lebreton, Study Scientist (Space Science Department of ESA, ESTEC, Noordwijk, Netherlands), G.E.N. Scoon, Study Manager (Future Projects Study Office, ESTEC, Noordwijk, Netherlands). Support was provided by members from the Operations Directorate and by members from the specialist divisions of the Technical Directorate of ESA. The NASA members responsible for the study were: J. Beckman, Study Manager (-6/88) (Jet Propulsion Laboratory, Pasadena, California, USA), G. Briggs (NASA Headquarters, Washington, D. C.), H. Brinton (NASA Headquarters, Washington, D.C.), R. Draper, Mariner Mark II Project Manager (Jet Propulsion Laboratory, Pasadena, California, USA), L. Horn (6/88-), Assistant Study Scientist (Jet Propulsion Laboratory, Pasadena, California, USA), W. Huntress (-6/88), Study Scientist (Jet Propulsion Laboratory, Pasadena, California, USA), C. Kohlhase (6/88-), Science and Mission Design Manager (Jet Propulsion Laboratory, Pasadena, California, USA), Support was also provided by D. Kindt, S. Kerridge, R. Stoller and other staff members of the Jet Propulsion Laboratory.
4. 'Deadband' is an attitude control term for the maximum angular deviation in spacecraft attitude that can occur before eliciting a corrective response from the attitude control subsystem (ACS). To reduce the frequency of these cycles (and thus reduce propellant consumption), the deadband during cruise was set to a conservative value of 20 mrad on each of the three axes. The size of the deadband can be reduced if more accurate pointing is required.
5. A special series of eleven papers on the Venus and Earth flybys is in *J. Geophys. Res. – Space Physics*, **106**, 30,099–30,279.
6. The interface altitude for atmospheric entry is taken to be 1,270 km.
7. All petal plots are shown in the MPF (MIMI Planning Frame) reference frame with the sun on the +X axis. The MPF is a rotating frame is defined as follows: (i) the Z-axis is along Saturn's polar axis (i.e. the Z-axis of the planet's body-fixed reference frame); (ii) the Y-axis is obtained as the unit vector along the cross product of the Z-axis and of the planet's center to Sun vector; (iii) the X-axis is computed as the cross product of the Y- and Z- unit vectors. On the XY plots, the inner dotted line is a circle whose radius corresponds to the semi-major axis of Titan's orbit.

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The authors are indebted to the many members of the *Cassini* and *Huygens* teams for much of the material reported in this paper. Due to the very broad scope of the scientific and engineering background discussed in this paper, a full review of all of the *Cassini* and *Huygens* literature is not possible within the constraints put on this article. Much material is in unpublished Project memoranda and reports. The main initiating documents are the reports of the study panels (ESA, 1985; 1988) and the announcements of opportunity by ESA and NASA (ESA, 1989; NASA, 1989; NASA, 1991). An early summary of the mission can be found in Lebreton (1991). Significant other literature includes books edited by Spilker (1997), and Wilson (1997). The definitive exposition is, of course, to be found in the following articles in this book together with a complementary volume to be published in the future. They provide in depth information on the motivation, design, and execution of the many investigations that constitute the *Cassini/Huygens* mission.

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## Appendix I: Saturn System Mythology, by Ladislav E. Roth

Until the middle of the nineteenth century, the satellites of Saturn bore numerical designations only. In 1847, John Herschel proposed that the satellites be named after Saturn's 'brothers and sisters, the Titans and Titanesses'. Titans and Titanesses were brothers and sisters not of Saturn, but of Kronos, Saturn's Greek counterpart. Hesiod, Homer's younger contemporary, gives us the earliest family history of the tribe of the Titans. Using some of Hesiod's own words, here is an outline of the story. In the beginning, there was Chaos, and after him came Gaia (the Earth). Gaia's first-born was Ouranos (the Sky), the 'one who matched her every dimension'. Gaia 'lay with Ouranos, and bore him Okeanos, Koios, Krios, Hyperion, Iapetus, Theia, Rhea, Themis, Mnemosyne, Phoebe, and Tethys'. Her youngest-born was the 'devious-devising Kronos, most terrible of her children'. Hesiod assigned the name Titans to the enumerated twelve children. Kronos, upon urging from Gaia, attacked his father Ouranos with the sickle she provided. Following the attack, Kronos became the supreme ruler of the world.

Kronos took Rhea as his wife. She bore him five children. Remembering the fate of his father, Kronos swallowed each child right after it was born. Zeus was the sixth-born. To save the baby, Rhea tricked her husband into swallowing a stone instead. At some later point, Kronos was made to regurgitate the stone and the five children he swallowed. (Hesiod does not say when and how.) With his siblings' help, Zeus initiated a rebellion against Kronos and the Titans. The Titans suffered a defeat in a terrible battle during which 'all earth was boiling'. Zeus imprisoned the defeated gods in Tartaros, 'a moldy place, at the uttermost edges of the monstrous earth' and, along with his Olympian allies, assumed the lordship over the world. Although Kronos' rule passed, it was long remembered as the Golden Age of mankind, when people 'lived as if they were gods, their hearts free from all sorrow, without hard work or pain'. Saturn, a Latin deity perhaps associated with farming, received some of the attributes of Kronos. The Romans adopted also the legend of the golden age. In their version, Saturn was the king of Italy in the long forgotten days when, as in the age of Kronos, life was all play and no work.

John Herschel gave the name Titan to the moon of Saturn which was discovered first and which happened to be the largest. The other four moons discovered in the seventeenth century he named Iapetus, Rhea, Dione, and Tethys. The minute inner satellites first observed by his father, John Herschel chose to name Enceladus and Mimas. Two satellites found in the nineteenth century received the names of Hyperion and Phoebe. The remaining satellites known at present were discovered in the twentieth century. They include Janus, Pan, Atlas, Prometheus, Pandora, Epimetheus, Telesto, Kalypso, and Helene. Of the eighteen named satellites, only Iapetus, Rhea, Tethys, Hyperion, and Phoebe bear the names of Saturn's 'brothers and sisters, the Titans and Titanesses'. A brief description of the meaning of the satellites' names is given below. The satellites are listed in the order of the increasing distance from Saturn.

**Pan-** Half-goat, half-human, the Arcadian Pan was worshipped as the patron of shepherds and as the personification of nature.

**Atlas-** Son of Iapetus. After the defeat of the Titans, Zeus ordered Atlas, 'at Earth's uttermost places, near the sweet-singing Hesperides' to uphold the vault of the sky. Hesiod refers probably to the Pillars of Hercules, the edge of the world known to the ancient Greeks

**Prometheus-** Hesiod presents Prometheus, son of Iapetus, as an immortal who sided with the mortals and as a prankster who liked to annoy his cousin Zeus. The ultimate annoyance was stealing 'the far-seen glory of weariless fire' and giving it to mankind. For this, Zeus fastened Prometheus to a mountain in the Caucasus, and he let loose on him 'the wing-spread eagle, and it was feeding on Prometheus' imperishable liver, which by night would grow back to size from which the spread-winged bird had eaten in the daytime'.

**Pandora-** The world's first woman. Creating Pandora was the punishment Zeus meted out to mankind for Prometheus' brazen acts of disobedience. Pandora arrived equipped with a jar that contained all the misfortunes, curses and plagues. Once the lid was lifted, the evil asserted itself in the world. 'Hope was the only spirit that stayed there, in the unbreakable closure of the jar, this was the will of the cloud-gathering Zeus'.

**Epimetheus-** Son of Iapetus, brother of Prometheus, husband of Pandora. Pictured as weak-minded, he is the one who lifted the lid on Pandora's jar.

**Janus-** An exalted Roman god, a figure of great antiquity and obscure origin. Always represented as having two faces, one looking forwards, the other backwards, Janus presided over the past, present, and future, over gates, doorways, entrances, and beginnings in general, and over war and peace. At every sacrifice, in every prayer, he was the first god invoked, taking precedence before Jupiter. When war was declared, the portals to the sanctuary of Janus on the Forum were opened. They were shut again on the declaration of peace. During the entire history of Rome, this happened on a handful of occasions only. As the most ancient of kings, Janus is supposed to have given the exiled Kronos a warm welcome in Italy, and to have offered him a share of the royal duties.

**Mimas-** One of the Giants, children of Gaia born of the blood of Ouranos.

**Enceladus-** One of the Giants, children of Gaia born of the blood of Ouranos. Giants, the last race of Hesiod's monsters, were beings of enormous size and invincible strength. Later depictions show them as having hideous faces, bristling beards, hanging hair, skins of wild animals for garments, tree trunks for weapons, and twin serpents for legs.

**Tethys-** The youngest of Titanesses, Tethys married her brother Okeanos, and bore him three thousand Okeanides, the 'light-stepping' sea-nymphs, and 'as many Rivers, the murmurously running sons'.

**Telesto-** A daughter of Tethys and Okeanos, an Okeanide.

**Kalypso-** A daughter of Tethys and Okeanos, an Okeanide. For Homer and other authors, she is a daughter of Atlas. In the course of the Odysseus' tortuous return to Ithaca, his ship ran aground on the fabled island of Ogygia, the home of the lonely Kalypso. Odysseus kept her company for seven years, after which he departed 'on a jointed raft'.

**Dione-** Dione presents a problem in the genealogy of the Greek gods. To Hesiod, she is a daughter of Tethys and Okeanos, and thus an Okeanide. She is mentioned in a number of other incarnations; for instance as a daughter of Ouranos and Gaia (this would make her a Titaness), or as a daughter of Kronos, or of Atlas. In some localities she was also worshipped as the wife of Zeus (instead of Hera).

**Helene-** The divinely beautiful wife of Menelaos, the king of Sparta, Helen (Helene) was abducted by Paris, the son of Priam, the king of Troy. Over Helen the Greeks fought the all-destructive Trojan War.

**Rhea-** A Titaness, married to her brother Kronos.

**Titan-** Not a single deity, but a generic name for the enumerated children of Ouranos and Gaia. (Ouranos and Gaia had more children, not just the Titans and the Giants.)

**Hyperion-** The fourth-born Titan, Hyperion took for a wife his sister Theia. 'Theia brought forth great Helios and shining Selene, the Sun and Moon, and Eos the Dawn who lights all earthly creatures and the immortal gods who hold the white heaven'. Solar and lunar deities, dominant in the affairs of other ancient civilizations, played a minor part in the religious life of ancient Greels.

**Iapetus-** Iapetus, a Titan, took Klymene, his niece, the 'light-stepping daughter of Okeanos, to be his wife'. Their sons were Atlas, Prometheus, and Epimetheus.

**Phoebe-** Phoebe, a Titanness, bore to her brother Koios the goddess Leto, 'the gentlest of all who are on Olympus. Leto, who had lain in the arms of Zeus, bore Apollo and Artemis, children more delightful than all the other Olympians'. In later antiquity, Phoebe was honored as the goddess of the Moon.