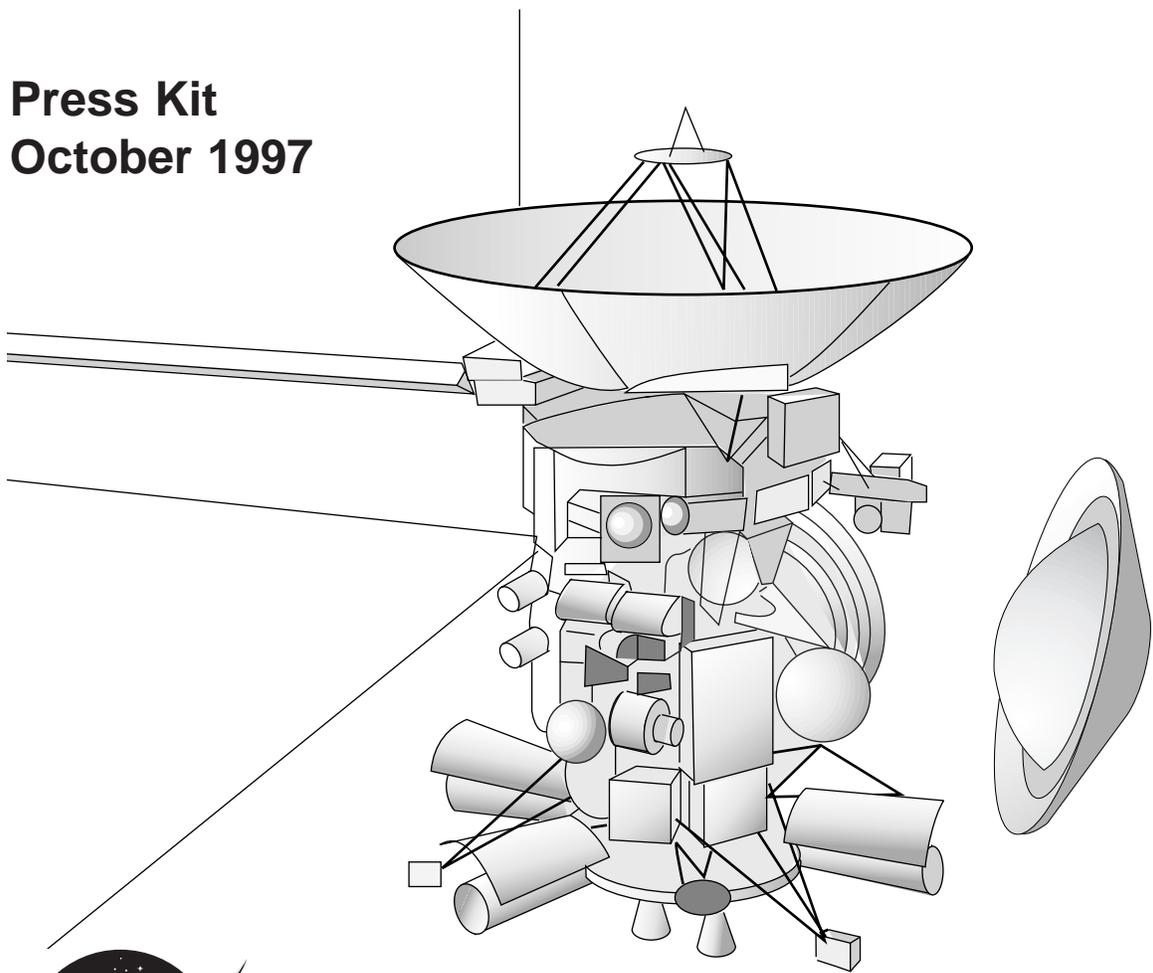


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

# Cassini Launch

Press Kit  
October 1997





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**RELEASE:**

**CASSINI TO SURVEY REALM OF SATURN AND TITAN**

The planet Saturn, its icy rings, the enigmatic moon Titan, other moons and the huge magnetic bubble that surrounds most of them are the prime scientific targets of the international Cassini mission, the most ambitious planetary exploration ever mounted. Final preparation of Cassini is now under way for a pre-dawn launch from Cape Canaveral, FL, on October 6, 1997.

The mission also entails the first descent of a probe to a moon of another planet, sending the Huygens probe to the surface of Saturn's moon Titan — by far the most distant landing ever attempted on another object in the solar system.

Cassini, in development since October 1989, is a cooperative endeavor of NASA, the European Space Agency (ESA) and the Italian Space Agency, or Agenzia Spaziale Italiana (ASI). The mission will send a sophisticated robotic spacecraft equipped with 12 scientific experiments to orbit Saturn for a four-year period and to study the Saturnian system in detail. The ESA-built Huygens probe that will parachute into Titan's thick atmosphere carries another six scientific instrument packages.

"Saturn, with its rings, 18 known moons and its magnetic environment, is a lot like a solar system in miniature form," said Dr. Wesley T. Huntress, NASA's associate administrator for space science. "It represents an unsurpassed laboratory where we can look for answers to many fundamental questions about the physics, chemistry and evolution of the planets and the conditions that give rise to life. Cassini and the Huygens probe represent our best efforts yet in our ongoing exploration of the solar system."

The launch period for Cassini's nearly seven-year journey to Saturn opens on October 6 and closes November 15, 1997. The launch is scheduled for October 13 at 4:55 a.m. Eastern Daylight Time (08:55 Universal Time). The launch window runs for 140 minutes each day and moves earlier by about six minutes daily. A U.S. Air Force Titan IVB/Centaur launch system, the most powerful launch vehicle in the U.S. fleet, will loft the Cassini spacecraft onto the interplanetary trajectory that will deliver the spacecraft to Saturn almost seven years later, on July 1, 2004. Cassini's primary mission concludes in July 2008.

In the early 1980s, the international science community selected a Saturn orbiter and Titan probe as the next logical step in the exploration of the solar system, similar to the Galileo mission to Jupiter. The Cassini orbiter and Huygens probe are the result of years of collaborative planning by space scientists and engineers in the United States and Europe.

Cassini is a follow-on mission to the brief reconnaissance of Saturn performed by the Pioneer 11 spacecraft in 1979 and the Voyager 1 and 2 encounters of 1980 and 1981. Those highly successful flybys produced volumes of new information, discoveries and questions about Saturn, its environs and its family of rings and moons. Those encounters, along with recent key

findings from the Hubble Space Telescope and ground-based observatories, continue to entice scientists who view the Saturnian system as a one-stop treasure trove with countless clues to the history of planetary and solar system evolution.

The mission is named for two 17th century astronomers. Italian-French astronomer Jean-Dominique Cassini (born Gian Domenico Cassini in his native Italy) made several key discoveries about Saturn between 1671 and 1684; he established that Saturn's rings are split largely into two parts by a narrow gap, known since as the Cassini Division. Dutch scientist Christiaan (cq) Huygens discovered Titan in 1655 and was responsible for many important Saturn findings.

Saturn is the second largest planet in the solar system. Like the other gaseous outer planets — Jupiter, Uranus and Neptune — its atmosphere is made up mostly of hydrogen and helium. Saturn's placid-looking, butterscotch-colored face masks a windswept atmosphere where jet streams blow at 1,800 kilometers per hour (1,100 miles per hour) and swirling storms roil just beneath the cloud tops. Spacecraft passing by Saturn found a huge and complex magnetic environment, called a magnetosphere, where trapped protons and electrons interact with each other, the planet, the rings and the surfaces of many of the moons.

The bright rings for which Saturn is best known have been found to consist of not just a few but hundreds of rings and ringlets, broad and thin, made up of ice and rock particles ranging in size from grains of sand to boxcars. The Voyager spacecraft observations in 1980 and 1981 found that the particles are herded into complicated orbits by the gravitational interaction of small moons unseen from Earth. Continuously jostled by their different orbital speeds and competing gravitational tugs from nearby moons and Saturn itself, the particles bump and grind away at each other, spreading out into a broad, thin sheet that is less than 100 meters (about 330 feet) thick, but almost as broad as the distance between the Earth and its Moon. So-called "shepherd moons" were found orbiting near the edges of some rings. Like sheepdogs working the edges of a flock, these moons gravitationally herd in and contain ring particles that would otherwise spread out into deep space.

More moons of greater variety orbit Saturn than any other planet. These natural satellites range from Titan, which is larger than either Mercury or Pluto and nearly the size of Mars, to bodies so puny that astronomers call them "moonlets." There are likely many more moons than the 18 that have been confirmed.

Although it is believed to be too cold to support life, haze-covered Titan is thought to hold clues to how the primitive Earth evolved into a life-bearing planet. It has an Earth-like, nitrogen-based atmosphere and a surface that many scientists believe probably features chilled lakes of ethane and methane (which may also pool in subsurface reservoirs). Scientists believe that the moon's surface is probably coated with the residue of a sticky brown organic rain. Titan's orange haze chemically resembles smog, and it is thought to be composed of naturally occurring, smoke-like hydrocarbon particles. Standing on Titan's surface beneath this orange sky, a visitor from Earth likely would find a cold, exotic world with a pungent odor reminiscent of a petroleum processing facility. Huygens will provide our first direct sampling of Titan's

atmospheric chemistry and the first detailed photographs of its hidden surface.

In maneuvers called gravity-assist swingbys, Cassini will fly twice past Venus then once each past Earth and Jupiter on its way to Saturn. The spacecraft's speed relative to the Sun increases as it approaches and swings past each planet, giving Cassini the cumulative boost it needs to reach its ultimate destination.

On November 6, 2004, Cassini will release the disc-shaped Huygens probe toward Titan. After a three-week ballistic freefall toward Titan, the 2.7-meter-diameter (8.9-foot), battery powered Huygens will enter Titan's atmosphere, deploy its parachutes and begin its scientific observations. Data gathered during Huygens' 2-1/2-hour descent through Titan's dense atmosphere will be radioed to the Cassini spacecraft and relayed to Earth. Instruments on the descent probe will measure the chemistry, temperature, pressure, density and energy balance in the atmosphere. As the probe breaks through the cloud deck, a camera will capture panoramic pictures of Titan. Titan's surface properties will be measured, and more than 500 images of the clouds and surface will be returned. In the final moments of descent, a spotlight will illuminate the surface for spectroscopic measurements of its composition.

If the probe survives landing — which should occur at a fairly low speed of about 25 kilometers per hour (15 miles per hour) — it may return data from Titan's surface, where the atmospheric pressure is 1.6 times that of Earth's and the temperature is -179 C (-290 F). The exact conditions it will encounter are unknown; the probe could touch down on solid ground, rock-hard ice, or even splash down in a lake of ethane and methane. One instrument onboard will discern whether Huygens is bobbing in liquid, and other instruments onboard could measure the chemical composition of that liquid.

During the course of the Cassini orbiter's mission, it will execute more than 40 targeted close flybys of Titan, many as close as 950 kilometers (about 590 miles) above the surface. This will permit high-resolution mapping of Titan's surface with the Titan imaging radar instrument, which can see through the opaque haze covering that moon to produce vivid photograph-like images.

The Cassini spacecraft, including the orbiter and Huygens probe, is the most complex interplanetary spacecraft ever built. Its sophisticated instruments are state-of-the-art and represent the best technical efforts of the United States and 16 European nations involved in the mission. Because of Cassini's challenging mission, long voyage and the value of its promised scientific return, each component and the system as a whole has undergone an unprecedented program of rigorous testing for quality and performance to assure the highest possible probability of mission success.

Because of the very dim sunlight at Saturn's orbit, solar arrays are not feasible. Electrical power is supplied to the orbiter by a set of radioisotope thermoelectric generators (RTGs), which convert the heat from the natural decay of plutonium-238, in the form of plutonium dioxide, to electricity for Cassini's systems. The same material is used in 117 radioisotope heater units (RHUs) placed on Cassini and Huygens to keep electronics systems at their operat-

ing temperatures. RHUs were most recently used on the Mars Pathfinder mission's Sojourner rover to keep the system from failing during cold Martian nights. Huygens will draw its electrical power from a set of five batteries during its entry and descent into Titan's atmosphere.

Telecommunications with Cassini during the mission will be carried out through the giant dish antennas of NASA's Deep Space Network, with complexes located in California, Spain and Australia. Cassini's high-gain antenna is provided by ASI. Data from the Huygens probe will be relayed to an ESA operations complex in Darmstadt, Germany. NASA's Lewis Research Center managed development of the Centaur upper stage.

Development of the Huygens probe was managed by an ESA team located at the European Space Technology and Research Center (ESTEC) in Noordwijk, the Netherlands. The Cassini orbiter was designed, developed and assembled at NASA's Jet Propulsion Laboratory (JPL), located in Pasadena, CA. JPL is a division of the California Institute of Technology. The overall mission is managed by JPL for NASA's Office of Space Science, Washington, DC.

[End of General Release]

# Media Services Information

## **NASA Television Transmission**

NASA Television is broadcast on the satellite GE-2, transponder 9C, C Band, 85 degrees west longitude, frequency 3880.0 MHz, vertical polarization, audio monaural at 6.8 MHz. The schedule for television transmissions for the Cassini launch will be available from the Jet Propulsion Laboratory, Pasadena, CA; Johnson Space Center, Houston, TX; Kennedy Space Center, FL, and NASA Headquarters, Washington, DC.

## **Status Reports**

Status reports on mission activities for Cassini will be issued by the Jet Propulsion Laboratory's Public Information Office. They may be accessed online as noted below. Daily audio status reports are available by calling (800) 391-6654 or (818) 354-4210.

## **Launch Media Credentialing**

Requests to cover the Cassini launch must be faxed in advance to the NASA Kennedy Space Center newsroom at (407) 867-2692. Requests must be on the letterhead of the news organization and must state the editor's assignment to cover the Cassini launch.

## **Briefings**

A pre-launch briefing on the mission and science objectives of Cassini will be held at Kennedy Space Center is planned at 10 a.m. EDT on October 4, 1997.

## **Internet Information**

Extensive information on Cassini, including an electronic copy of this press kit, press releases, fact sheets, status reports and images, is available from the Jet Propulsion Laboratory's World Wide Web home page at <http://www.jpl.nasa.gov/> . The Cassini Program also maintains a home page at <http://www.jpl.nasa.gov/cassini> .

# Quick Facts

## Spacecraft

Spacecraft dimensions: 6.7 meters (22 feet) high; 4 meters (13.1 feet) wide

Weight: 5,712 kilograms (12,593 pounds) with fuel, Huygens probe, adapter, etc;

2,125 kilograms (4,685 pounds) unfueled orbiter alone

Science instruments: camera; magnetic field studies; dust and ice grain analysis; infrared energy measurement; chemical composition of Saturn, its moons and rings; neutral and charged particle measurement; radar mapping; and radio wave searches

Power: 885 watts (633 watts at end of mission) from radioisotope thermoelectric generators

## Huygens Probe

Probe dimensions: 2.7 meters (8.9 feet) in diameter

Weight: 320 kilograms (705 pounds)

Science instruments: spectrometer to identify atmospheric makeup; aerosol collector for chemical analysis; imager; sensors to measure atmospheric structure; wind speed measurements; sensors to measure conditions at impact site.

## Launch Vehicle

Type: Titan IVB/ Centaur

Weight: 1 million kilograms (2.2 million pounds)

## Mission

Launch: October 13, 1997 from Cape Canaveral Air Station, FL. Primary launch period runs through November 15, 1997. On October 13, 140-minute window opens at 4:55 a.m. EDT. Opening of window moves about 6 minutes earlier daily thereafter

Venus flybys: April 25, 1998 at 300 km (190 mi); June 23, 1999 at 1,530 km (950 mi)

Earth flyby: August 17, 1999 at 800 km (500 mi) or higher

Jupiter flyby: December 30, 2000 at 10 million km (6 million mi)

Saturn arrival date: July 1, 2004

Huygens probe Titan entry date: November 27, 2004

Distance traveled to reach Saturn: 3.5 billion km (2.2 billion mi)

Saturn's average distance from Earth: 1.43 billion km (890 million mi)

One-way light time to Saturn during orbital tour: 68 to 85 minutes

Huygens' entry speed into Titan's atmosphere: 20,000 kph (about 12,400 mph)

## Program

Partners: NASA, the European Space Agency (ESA), Italian Space Agency (Agenzia Spaziale Italiana (ASI)); total of 17 countries involved

U.S. states in which Cassini work was carried out: 33

Number of people who have worked on some portion of Cassini/Huygens: More than 5,000

Cost of mission: \$1.422B pre-launch development; \$755M mission operations; \$54M tracking; \$422M launch vehicle; \$500M ESA; \$160M ASI; total about \$3.3 billion

# Saturn at a Glance

## General

- One of five planets known to the ancients; Roman god of agriculture, also linked to Kronos, Greek god of time; father of Jupiter, king of the gods
- Yellowish color; at times the 5th brightest planet in night sky

## Physical Characteristics

- Second largest planet in the solar system, after Jupiter
- Equatorial diameter 120,536 kilometers (74,898 miles) at cloud tops; polar diameter 108,728 kilometers (67,560 miles), making it the most oblate planet
- Density 0.69 (water = 1)
- Volume 764 times that of Earth, but only 95 times more massive

## Orbit

- Sixth planet from the Sun, between Jupiter and Uranus
- Mean distance from Sun 1.43 billion kilometers (890 million miles)
- Brightness of sunlight at Saturn 1 percent of that at Earth
- Revolves around Sun once every 29.42 Earth years
- Saturn's interior rotates once every 10 hours, 39.4 minutes
- Poles tilted 29 degrees

## Environment

- Saturn's atmosphere above the clouds is approximately 94 percent hydrogen and 6 percent helium
- Winds near Saturn's equator blow toward east at 500 meters per second (1,100 miles per hour)
- Temperature at Saturn's cloud tops -139 C (-218 F)

## Previous Exploration

- Pioneer 11 flyby September 1, 1979
- Voyager 1 flyby November 12, 1980
- Voyager 2 flyby August 25, 1981

## Rings

- Saturn's main ring system would barely fit in the space between Earth and its Moon
- B-ring often contains radial spokes of dust-sized material which are regenerated frequently
- Cassini Division between the B-ring and A-ring is sparsely populated with ring material
- E-ring is densest at the orbit of Enceladus and may be fed by Enceladus eruptions.

## The Rings of Saturn

Ring	Distance	Width
D	66,970 km (41,610 mi)	7,540 km (4,690 mi)
C	74,510 km (46,300 mi)	17,490 km (10,870 mi)
B	92,000 km (57,170 mi)	25,580 km (15,890 mi)
A	122,170 km (75,910 mi)	14,610 km (9,080 mi)
F	140,180 km (87,100 mi)	50 km (30 mi)
G	170,180 km (105,740 mi)	500 to several 1,000s km (300 to several 1,000s mi)
E	181,000 km (112,000 mi)	302,000 km (188,000 mi)

*Distance is from Saturn's center to closest edge of ring*

## The Known Moons of Saturn (18)

Moon	Diameter	Distance	Discoverer
Pan	20 km (10 mi)	133,583 km (83,004 mi)	1990: Showalter
Atlas	32 km (20 mi)	137,640 km (85,530 mi)	1980: Terrile (Voyager)
Prometheus	100 km (62 mi)	139,350 km (86,590 mi)	1980: Collins (Voyager)
Pandora	84 km (52 mi)	141,700 km (88,050 mi)	1980: Collins (Voyager)
Epimetheus	119 km (74 mi)	151,422 km (94,089 mi)	1966: Walker
Janus	178 km (111 mi)	151,472 km (94,120 mi)	1966: Dolfus
Mimas	392 km (244 mi)	185,520 km (115,280 mi)	1789: Herschel
Enceladus	499 km (310 mi)	238,020 km (147,900 mi)	1789: Herschel
Tethys	1,060 km (658 mi)	294,660 km (183,090 mi)	1684: Cassini
Telesto	22 km (14 mi)	294,660 km (183,090 mi)	1980: Smith
Calypso	20 km (12 mi)	294,660 km (183,090 mi)	1980: Smith
Dione	1,120 km (696 mi)	377,400 km (234,500 mi)	1684: Cassini
Helene	35 km (22 mi)	378,400 km (235,100 mi)	1980: Laques and Lecacheux
Rhea	1,528 km (949 mi)	527,040 km (327,490 mi)	1672: Cassini
Titan	5,150 km (3,200 mi)	1,221,850 km (759,220 mi)	1655: Huygens
Hyperion	283 km (176 mi)	1,481,100 km (920,300 mi)	1848: Bond
Iapetus	1,436 km (892 mi)	3,561,300 km (2,212,900 mi)	1671: Cassini
Phoebe	220 km (140 mi)	12,952,000 km (8,048,000 mi)	1898: Pickering

Pan "PAN"

Atlas "AT-luss"

Prometheus "pro-MEE-thee-uss"

Pandora "pan-DOR-uh"

Epimetheus "epp-ee-MEE-thee-uss"

Janus "JANE-uss"

Mimas "MY-muss"

Enceladus "en-SELL-uh-duss"

Tethys "TEE-thiss"

Telesto "tel-LESS-toe"

Calypso "kuh-LIP-soh"

Dione "DIE-oh-nee"

Helene "huh-LEE-nee"

Rhea "REE-uh"

Titan "TIE-tun"

Hyperion "high-PEER-ee-on"

Iapetus "eye-APP-eh-tuss"

Phoebe "FEE-bee"

# Why Saturn?

Saturn offers a rich scientific environment to explore. The planet and the ring system serve as a physical model for the disc of gas and dust that surrounded the early Sun and from which the planets formed. The success of searches for other planetary systems elsewhere in our galaxy partly depends upon how well we understand the early stages of formation of planets.

Detailed knowledge of the history and processes now occurring on Saturn's elaborately different moons will provide valuable data for studying how each of the solar system's planets evolved to their present states. Represented among Saturn's collection of moons is a huge variety of chemical, geologic and atmospheric processes. Physics and chemistry are the same everywhere, and the knowledge gained about Saturn's magnetosphere or Titan's atmosphere will have applications here on Earth.

Chief among Cassini's goals within Saturn's system, however, is the unmasking of Titan.

After decades of speculation and experiment in the modern age, scientists still seek fundamental clues to the question of how life began on Earth. Most experts suspect that life arose by chance combinations of complex carbon compounds in a primeval soup. But all studies of life's origin are hampered by ignorance about the chemical circumstances on the young Earth.

In our solar system, only Earth and Titan have atmospheres rich in nitrogen. Earth's siblings in the inner solar system, Venus and Mars, possess carbon-dioxide atmospheres, while Jupiter and Saturn resemble the Sun in their high content of hydrogen and helium. Hydrocarbons like the methane present on Titan may have been abundant on the young Earth.

The importance of Titan in this connection is that it may preserve, in deep-freeze, many of the chemical compounds that preceded life on Earth. Some scientists believe we will find that Titan shares more in common with the early Earth than Earth itself does today.

The results from Cassini's instruments and the Huygens probe, along with the results of our continuing explorations of Mars, Europa and the variety of life-bearing environments on Earth, will significantly enhance scientific efforts to solve the mystery of our origins.

## **Cassini and Planetary Exploration**

The Cassini-Huygens mission is an enterprise that, from the initial vision to the completion of the mission, will span nearly 30 years. The formal beginning was in 1982, when a joint working group was formed by the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Science in the United States. The charter of the group was to study possible modes of cooperation between the U.S. and Europe in the field of planetary science. Their precept was that the mission would be beneficial for the scientific, technological and industrial sectors of their countries. As a result of their involvement in the studies, European scientists proposed a Saturn orbiter and Titan probe

mission to the European Space Agency (ESA), suggesting a collaboration with NASA.

In 1983, the U.S. Solar System Exploration Committee recommended that NASA include a Titan probe and radar mapper in its core program and also consider a Saturn orbiter. In 1984-85, a joint NASA/ESA assessment of a Saturn orbiter-Titan probe mission was completed. In 1986, ESA's Science Program Committee approved Cassini for initial Phase A study, with a conditional start in 1987.

In 1987-88, NASA carried out further work on designing and developing the standardized Mariner Mark II spacecraft and a set of outer planets missions that would be accomplished with the new spacecraft line. The program was an early effort to reduce the costs of planetary exploration by producing multiple spacecraft for different missions but made with the basic spacecraft components off the same assembly line. Cassini and the Comet Rendezvous/Asteroid Flyby (CRAF) were the first two missions chosen for further study. At the same time in Europe, a Titan probe Phase A study was carried out by ESA in collaboration with a European industrial consortium led by Marconi Space Systems. The Titan probe was renamed Huygens by ESA as its first medium-sized mission of its Horizon 2000 space science program.

In 1989, funding for CRAF and Cassini was approved by the U.S. Congress. NASA and ESA simultaneously released announcements of opportunity for scientists to propose scientific investigations for the missions. In 1992, a funding cap was placed on the Mariner Mark II program, effectively ending the new spacecraft line and, at the same time, canceling the CRAF mission. Cassini was restructured to cut the cost of the mission and to simplify the spacecraft and its operation.

The design of Cassini is the result of extensive tradeoff studies which considered cost, mass, reliability, durability, suitability and availability of hardware. To forestall the possibility of mechanical failures, moving parts were eliminated from the spacecraft wherever the functions could be performed satisfactorily without them. Thus, early designs that included moving science instrument platforms or turntables were discarded in favor of instruments fixed to the spacecraft body, whose pointing requires rotation of the entire spacecraft. Tape recorders were replaced with solid-state recorders. Mechanical gyroscopes were replaced with hemispherical resonator gyroscopes. An articulated probe relay antenna was discarded in favor of using the high-gain antenna to capture the radio signal of the Huygens probe. A deployable high-gain antenna of the type used for Galileo was considered and abandoned.

Project engineers, both those who designed and built the hardware and those who operate the spacecraft, relied heavily on extensive past experience to provide a spacecraft design more sophisticated, reliable and capable than any other spacecraft ever built for exploration of the planets. Because of that care in design, the Cassini spacecraft is easier to operate and will return more scientific data about its targets than has been possible in any previous planetary mission.

The research and development that Cassini has funded has provided key technologies that have enabled many of NASA's new "faster, better, cheaper" missions. All of NASA's new

Discovery class missions such as Mars Pathfinder so far have used innovative technology derived from Cassini, and spacecraft being developed for NASA's New Millennium rely heavily upon fundamental new technologies brought forth by Cassini.

It is the ability to perform synergistic science that sets Cassini apart from other missions. The very complex interactions that are in play in systems such as those found at Jupiter and Saturn can best be addressed by instrument platforms such as Galileo and Cassini. Many phenomena to be studied are often sensitive to a large number of parameters; a measurement might have to take into account simultaneous dependencies on location, time, directions to the Sun and planet, the orbital configurations of certain moons, magnetic longitude and latitude and solar wind conditions. To deal with such complexity, the right types of instruments must be on the spacecraft to make all the necessary and relevant measurements, and all the measurements must be made essentially at the same time. Identical conditions very seldom recur. A succession or even a fleet of less well equipped spacecraft could not obtain the same result. The need for a broadly based, diverse collection of instruments is the reason why the Cassini-Huygens spacecraft is so large.

The Cassini and Huygens missions, featuring the intertwined work of NASA, ESA and ASI, have become models for future international space science cooperation.

# The Saturn System

Saturn is easily visible to the naked eye, and was known to ancient peoples around the world. It was not until the invention of the telescope, however, that Saturn's characteristic rings began to come into focus.

## Historical Observations

The Italian astronomer Galileo was the first to look at Saturn through a telescope in 1609-10. Viewed through Galileo's crude instrument, Saturn was a puzzling sight. Unable to make out the rings, Galileo thought he saw two sizable companions close to the planet. Having recently discovered the major moons of Jupiter, he supposed that Saturn could have large moons, too. "... [T]o my very great amazement, Saturn was seen to me to be not a single star, but three together, which almost touch each other," he wrote at the time.

Galileo was even more astonished when, two years later, he again looked at Saturn through his telescope only to find that the companion bodies had apparently disappeared. "I do not know what to say in a case so surprising, so unlooked for and so novel," he wrote in 1612. The rings were simply "invisible" because he was now viewing them edge-on. Two years later, they again reappeared, larger than ever. He concluded that what he saw were some sort of "arms" that grew and disappeared for unknown reasons. He died never knowing that he had been the first to observe Saturn's rings.

Nearly half a century later, the Dutch scientist Christiaan Huygens solved the puzzle that vexed Galileo. Thanks to better optics, Huygens was able to pronounce in 1659 that the companions or arms decorating Saturn were not appendages, but rather the planet "is surrounded by a thin, flat ring, which nowhere touches the body." His theory was received with some opposition, but was confirmed by the observations of Robert Hooke and Italian-French astronomer Jean Dominique Cassini.

While observing Saturn, Huygens also discovered the moon Titan. A few years later, Cassini added several other key Saturn discoveries. Using new telescopes, Cassini discovered Saturn's four other major moons — Iapetus, Rhea, Tethys and Dione.

In 1675, Cassini discovered that Saturn's rings are split largely into two parts by a narrow gap — known since as the "Cassini Division." In the 19th century, J. E. Keeler, pursuing theoretical studies developed by James Clerk Maxwell, showed that the ring system was not a uniform sheet but made up of small particles that orbited Saturn.

The first detection of Saturn's magnetic field came with the flyby of Saturn by NASA's Pioneer 11 spacecraft in 1979. Then, in 1980 and 1981, the NASA Voyager 1 and Voyager 2 spacecraft flew through Saturn's system to reveal storms and subtle latitudinal banding in the planet's atmosphere, several more small moons and a breathtaking collection of thousands of ringlets. The Voyagers found ring particles ranging in size from nearly invisible dust to icebergs

the size of a house. The spacing and width of the ringlets were discovered to be orchestrated at least in part by gravitational tugs from a retinue of orbiting moons and moonlets, some near ring edges but most far beyond the outermost main rings. Voyager instruments confirmed a finding from ground-based instruments that the rings contain water ice, which may cover rocky particles.

Saturn has been a frequent target of the Hubble Space Telescope, which has produced stunning views of long-lived hurricane-like storms in Saturn's atmosphere. The world's major telescopes, including Hubble, were recently trained on Saturn to observe the phenomenon known to astronomers as a Saturn ring plane crossing. The rings were seen edge-on from Earth's perspective on May 22 and August 10, 1995, and on February 11, 1996. Ring plane crossings provide astronomers with unique views of Saturn's system.

These observations showed that the ring plane was not absolutely flat; the tilt of the F-ring distorts the appearance of the rings, causing one side to appear brighter than the other during ring plane crossings. Searches for new moons turned up several suspects, but most are now believed to be bright "knots" in the F-ring. Of particular interest were these ring arcs, natural "satellites" in the F-ring that appeared cloud-like and spread over a small area, instead of sharp pinpoints. The origin of these clumps of material in the F-ring is not well understood.

The faint, outermost E-ring is also easier to detect when viewed edge-on due to the greater amount of material in the line-of-sight. Thus, observations made over the course of the ring plane crossing provided new information on the thickness of the rings. New information gathered on the location and density of material in the rings was used by designers to plan the most advantageous and safest course for Cassini's flight through the E-ring upon arrival at Saturn in 2004.

The Hubble Space Telescope is an important tool for studying Saturn, its rings, moons and magnetosphere in support of the Cassini mission. Hubble observations of Saturn's atmosphere were made after storms were discovered by ground-based observers. First in 1990 and again in 1994, apparent upwellings of ammonia clouds appeared and then were spread around the planet by prevailing winds.

Hubble observations of Titan indicate that color differences in Titan's hemispheres seen during the Voyager flybys in 1980 and 1981 have since reversed themselves. Some Hubble observations have studied chemical processes in Titan's atmosphere. Images made in the infrared have looked through Titan's clouds and allowed some mapping of its surface. Hubble has also contributed new information about the processes in Saturn's magnetosphere through ultraviolet measurements of Saturn's auroras.

Scientists using Hubble expect to study the planet and the ring system as it opens up to our view during the course of Cassini's cruise to the planet. Hubble investigations will place Cassini results in the context of the decades-long studies of the planet and help direct Cassini instruments for studies of Saturn's system during its orbital tour.

## Saturn's Place in the Solar System

Studies of star formation indicate that our solar system formed within a giant collection of gases and dust, drawn together by gravitational attraction and condensed over many millions of years into many stars. The giant gas cloud condensed into rotating pools of higher density in a process called gravitational collapse. These rotating pools of material condensed more rapidly until their temperatures and densities were great enough to form stars. Surrounding each new star, the leftover material flattened into a disc rotating approximately in the plane of the star's equator. This material can eventually form planets — and this is apparently what occurred in our solar system.

The composition of the planets is largely controlled by their temperatures, which in turn is determined by their distances from the Sun. Compounds with high melting points were the first to condense, followed by silicates. These formed the rocky cores of all the planets.

While hydrogen is the predominant element in the universe and in our solar system, other gases are present, including water, carbon dioxide and methane. As ices, these predominate in the cooler outer solar system. Gases also collected as envelopes around the planets and moons. (Where conditions are right, large quantities of water in its liquid state can form, as exhibited by Earth's oceans, Mars' flood plains and a possible ocean beneath the surface of Europa, a moon of Jupiter.)

The large outer planets contain much of the primordial cloud's gases not trapped by the Sun. Hydrogen is the most abundant material in the Sun and in all the large gaseous planets — Jupiter, Saturn, Uranus and Neptune. Each of these giant planets has many moons. These moons form systems of natural satellites, creating the equivalent of miniature solar systems around the gas giants formed by processes similar to those responsible for the system around the Sun.

Saturn is similar to Jupiter in size, shape, rotational characteristics and moons, but Saturn is less than one-third the mass of Jupiter and is almost twice as far from the Sun. Saturn radiates more heat than it receives from the Sun. This is true of Jupiter as well, but Jupiter's size and cooling rate suggest that it is still warm from the primordial heat generated from condensation during its formation. Slightly smaller Saturn, however, has had time to cool — so some mechanism, such as helium migrating to the planet's core, is needed to explain its continuing radiation of heat.

Voyager measurements found that the ratio of helium to molecular hydrogen in Saturn is 0.06, compared to Jupiter's value of 0.13 (which is closer to the solar abundance and that of the primordial solar nebula). Helium depletion in Saturn's upper atmosphere is believed to result from helium raining down to the lower altitudes; this supports the concept of helium migration as the heat source in Saturn. Cassini's measurements of Saturn's energy, radiation and helium abundance will help explain the residual warmth.

Saturn's visible features are dominated by atmospheric clouds. They are not as distinct

as Jupiter's clouds, primarily because of a haze layer covering the planet that is a result of cooler temperatures due to the weaker incoming sunlight. This reduced solar radiation, and correspondingly greater influence from escaping internal heat, lead to greater wind velocities on Saturn. Both Saturn's and Jupiter's weather are thus driven by heat from below.

## **The Planet Saturn**

Saturn is the sixth planet from the Sun. Compared with Earth, Saturn is 9.5 times farther away from the Sun. From Saturn, the Sun is about 1/10th the size of the Sun we see from Earth. Sunlight spreads as it travels through space; an area on Earth receives 90 times more sunlight than an equivalent area on Saturn. Because of this fact, the same light-driven chemical processes in Saturn's atmosphere take 90 times longer than they would at Earth. The farther away from the Sun, the slower a planet travels in its orbit, and the longer it takes to complete its orbit about the Sun. Saturn's year is equal to 29.46 Earth years.

Saturn's orbit is not circular but slightly elliptical in shape; as a result, Saturn's distance from the Sun changes as it orbits the Sun. This elliptical orbit causes a small change in the amount of sunlight that reaches the surface of this gaseous planet at different times in the Saturn year, and may affect the planet's upper atmospheric composition over that period.

Saturn's period of rotation around its axis depends on how it is measured. The cloud tops show a rotation period of 10 hours, 15 minutes at the equator, but the period is 23 minutes longer at higher latitudes. A radio signal that has been associated with Saturn's magnetic field shows a period of 10 hours, 39.4 minutes.

This high rotation rate creates a strong centrifugal force that causes an equatorial bulge and a flattening of Saturn's poles. As a result, Saturn's cloud tops at the equator are about 60,330 kilometers (37,490 miles) from the center, while the cloud tops at the poles are only about 54,000 kilometers (33,550 miles) from the center. Saturn's volume is 764 times the volume of Earth.

Saturn has the lowest density of all the planets because of its vast, distended, hydrogen-rich outer layer. Like the other giant planets, Saturn contains a liquid core of heavy elements including iron and rock of about the same volume as Earth, but having three or more times the mass of Earth. This increased density is due to compression resulting from the pressure of the liquid and atmospheric layers above the core, and is caused by gravitational compression of the planet.

The core of molten rocky material is believed to be covered with a thick layer of metallic liquid hydrogen and, beyond that, a layer of molecular liquid hydrogen. The great overall mass of Saturn produces a very strong gravitational field, and at levels just above the core the hydrogen is compressed to a state that is liquid metallic, which conducts electricity. (On Earth, liquid hydrogen is usually made by cooling the hydrogen gas to very cold temperatures, but on Saturn, liquid hydrogen is very hot and is formed under several million times the atmospheric pressure found at Earth's surface.) This conductive liquid metallic hydrogen layer, which is also

spinning with the rest of the planet, is believed to be the source of Saturn's magnetic field. Turbulence or convective motion in this layer of Saturn's interior may create Saturn's magnetic field .

One unusual characteristic of Saturn's magnetic field is that its axis is the same as that of the planet's rotation. This is different from that of five other notable magnetic fields: those of Mercury, Earth, Jupiter, Uranus and Neptune. Current theory suggests that when the axes of rotation and magnetic field are aligned, the magnetic field cannot be maintained. Scientists do not understand the alignment of Saturn's strong magnetic field with its rotation axis, which does not fit with theories of how planets' magnetic fields are generated.

On Earth, there is a definite separation between the land, the oceans and the atmosphere. Saturn, on the other hand, has only layers of hydrogen that transform gradually from a liquid state deep inside into a gaseous state in the atmosphere, without a well-defined boundary. This is an unusual condition that results from the very high pressures and temperatures found on Saturn. Because the pressure of the atmosphere is so great, the atmosphere is compressed so much where the separation would be expected to occur that it actually has a density equal to that of the liquid. This condition is referred to as "supercritical." It can happen to any liquid and gas if compressed to a point above critical pressure. Saturn thus lacks a distinct surface; when making measurements, scientists use as a reference point the altitude where the pressure is 1 bar (or one Earth atmosphere). This pressure level is near Saturn's cloud tops.

The major component of Saturn's atmosphere is hydrogen gas. If the planet were composed solely of hydrogen, there would not be much of interest to study. However, the composition of Saturn's atmosphere includes 6 percent helium gas by volume; in addition, 1/10,000th of 1 percent is composed of other trace elements. Using spectroscopic analysis, scientists find that these atmospheric elements can interact to form ammonia, phosphine, methane, ethane, acetylene, methylacetylene and propane. Even a small amount is enough to freeze or liquefy and make clouds of ice or rain possessing a variety of colors and forms.

With the first pictures of Saturn taken by the Voyager spacecraft in 1980, the clouds and the winds were seen to be almost as complex as those that Voyager found on Jupiter just the year before. Scientists have made an effort to label the belts and zones seen in Saturn's cloud patterns. The banding results from convective flows in the atmosphere driven by temperature — very much the same process that occurs in Earth's atmosphere, but on a grander scale and with a different heat source.

Saturn has different rotation rates in its atmosphere at different latitudes. Differences of 1,500 kilometers per hour (more than 900 miles per hour) were seen between the equator and nearer the poles, with higher speeds at the equator. This is five times greater than the wind velocities found on Jupiter.

Saturn's cloud tops reveal the effects of temperature, winds and weather many kilometers below. Hot gases rise. As they rise, they cool and can form clouds. As these gases cool, they begin to sink: this convective motion is the source of the billowy clouds seen in the cloud

layer. Cyclonic storms observed in the cloud tops of Saturn are much like the smaller versions we see in weather satellite images of Earth's atmosphere.

Temperature variations in Saturn's atmosphere are the driving force for the winds and thus cloud motion. The lower atmosphere is hotter than the upper atmosphere, causing gases to move vertically, and the equator is warmer than the poles because it receives more direct sunlight. Temperature variations, combined with the planet's rapid rotation rate, are responsible for the fast horizontal motion of winds in the atmosphere.

## **Titan**

Titan presents an environment which appears to be unique in the solar system, with a thick organic hazy atmosphere containing organic (or carbon-based) compounds, an organic ocean or lakes and a rich soil filled with frozen molecules similar to what scientists believe led to the origin of life on Earth. In the three centuries since the discovery of Titan we have come to see it as a world strangely similar to our own, yet located almost 1-1/2 billion kilometers (900 million miles) from the Sun. With a thick, nitrogen-rich atmosphere, possible seas and a tar-like permafrost, Titan is thought to harbor organic compounds that may be important in the chain of chemistry that led to life on Earth.

Titan has been described as having an environment similar to that of Earth before biological activity forever altered the composition of Earth's atmosphere. The major difference on Titan, however, is the absence of liquid water and Titan's very low temperature. Thus there is no opportunity for aqueous chemistry at Earth-like temperatures — considered crucial for the origin of life as we know it. Scientists say the surface temperatures on Titan are thought to be cold enough to preclude any biological activity whatsoever at Titan.

As on Earth, the dominant atmospheric constituent in Titan's atmosphere is nitrogen. Methane represents about 6 percent of the atmospheric composition. Titan's surface pressure is 1.6 bars — more than 50 percent greater than that on Earth, despite Titan's smaller size. The surface temperature was found by Voyager to be -179 C (-290 F), indicating that there is little greenhouse warming.

The opacity of Titan's atmosphere is caused by naturally produced photochemical smog. Voyager's infrared spectrometer detected many minor constituents produced primarily by photochemistry of methane, which produces hydrocarbons such as ethane, acetylene and propane. Methane also interacts with nitrogen atoms, forming "nitriles" such as hydrogen cyanide. With Titan's smoggy sky and distance from the Sun, a person standing on Titan's surface in the daytime would experience a level of daylight equivalent to about 1/1,000th the daylight at Earth's surface.

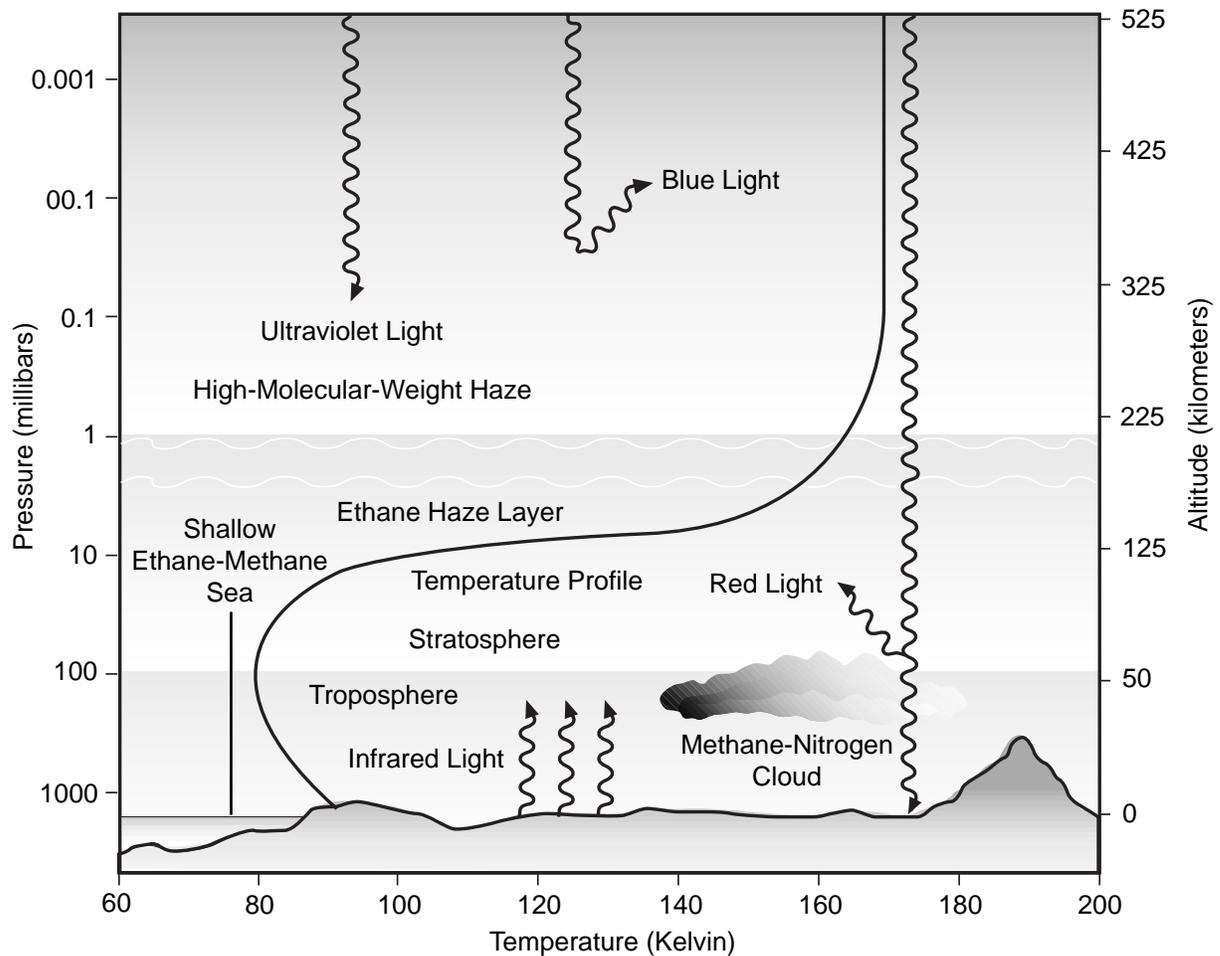
What is the source of molecular nitrogen, the primary constituent of Titan's atmosphere as we see it today? Was the molecular nitrogen accumulated as Titan formed, or was it the byproduct of ammonia that formed with Titan? Did it come from comets? This important question can be investigated by looking for argon in Titan's atmosphere. Both argon and nitrogen

condense at similar temperatures. If molecular nitrogen from the solar nebula — the cloud of gas that formed the Sun — was the source of nitrogen on Titan, then the ratio of argon to nitrogen in the solar nebula should be preserved on Titan. Such a finding would mean that we have truly found a sample of the "original" planetary atmosphere.

Some of the hydrocarbons found at Titan spend time as the aerosol haze in the atmosphere that obscures the surface. Many small molecules of compounds such as hydrogen cyanide and acetylene combine to form larger chains in a process called polymerization, resulting in additional aerosols. Eventually they drift to Titan's surface. Theoretically the aerosols should accumulate on the surface and, over the life of the solar system, produce a global ocean of ethane, acetylene, propane and other constituents with an average depth of up to 1 kilometer (about two-thirds of a mile). A large amount of liquid methane mixed with ethane could theoretically provide an ongoing source of methane in the atmosphere, similar to the way oceans on Earth supply water to the atmosphere. Radar and near-infrared data from ground-based studies show, however, that there is no global liquid ocean on Titan, although there could be lakes and seas. Titan appears to have winds.

The surface of Titan was not visible to Voyager at the wavelengths available to Voyager's cameras. What knowledge exists about the appearance of the surface of Titan comes from Earth-based radar measurements and more recent images acquired with the Hubble Space Telescope at wavelengths longer than those of Voyager's cameras. Hubble images from 1994 and later reveal brightness variations suggesting that Titan has a large continent-sized region on its surface that is distinctly brighter than the rest of the surface at both visible and near-infrared wavelengths. Preliminary studies suggest that a simple plateau or elevation change of Titan's surface cannot explain the image features; the brightness differences must be partly due to a different composition and/or roughness of material. Like other moons in the outer solar system, Titan is expected to have a predominantly water ice crust. Water at the temperatures found in the outer solar system is as solid and strong as rock. There are weak spectral features that suggest ice on Titan's surface, but some dark substance is also present. Scientists conclude that something on the surface is masking the water ice.

Titan's size alone suggests that it may have a surface similar to Jupiter's moon Ganymede — somewhat modified by ice tectonics, but substantially cratered and old. If Titan's tectonic activity is no more extensive than that of Ganymede, circular crater basins may provide storage for lakes of liquid hydrocarbons. Impacting meteorites would create a layer of broken, porous surface materials, called regolith, which may extend to a depth of 1 to 3 kilometers (about 1 to 2 miles) This regolith could provide subsurface storage for liquid hydrocarbons as well. In contrast to Ganymede, Titan may have incorporated as much as 15 percent ammonia as it formed in the colder region of Saturn's orbit. As Titan's water-ice surface froze, ammonia-water liquid would have been forced below the surface. This liquid will be buoyant relative to the surface water-ice crust, however; ammonia-water magma thus may have forced its way along cracks to the surface, forming exotic surface features. Density measurements suggest that Titan is made up of roughly half rocky silicate material and half water ice. Methane and ammonia could have been mixed with the water ice during Titan's formation. The formation of Titan by accretion was at temperatures warm enough for Titan to differentiate; rocky material sank to

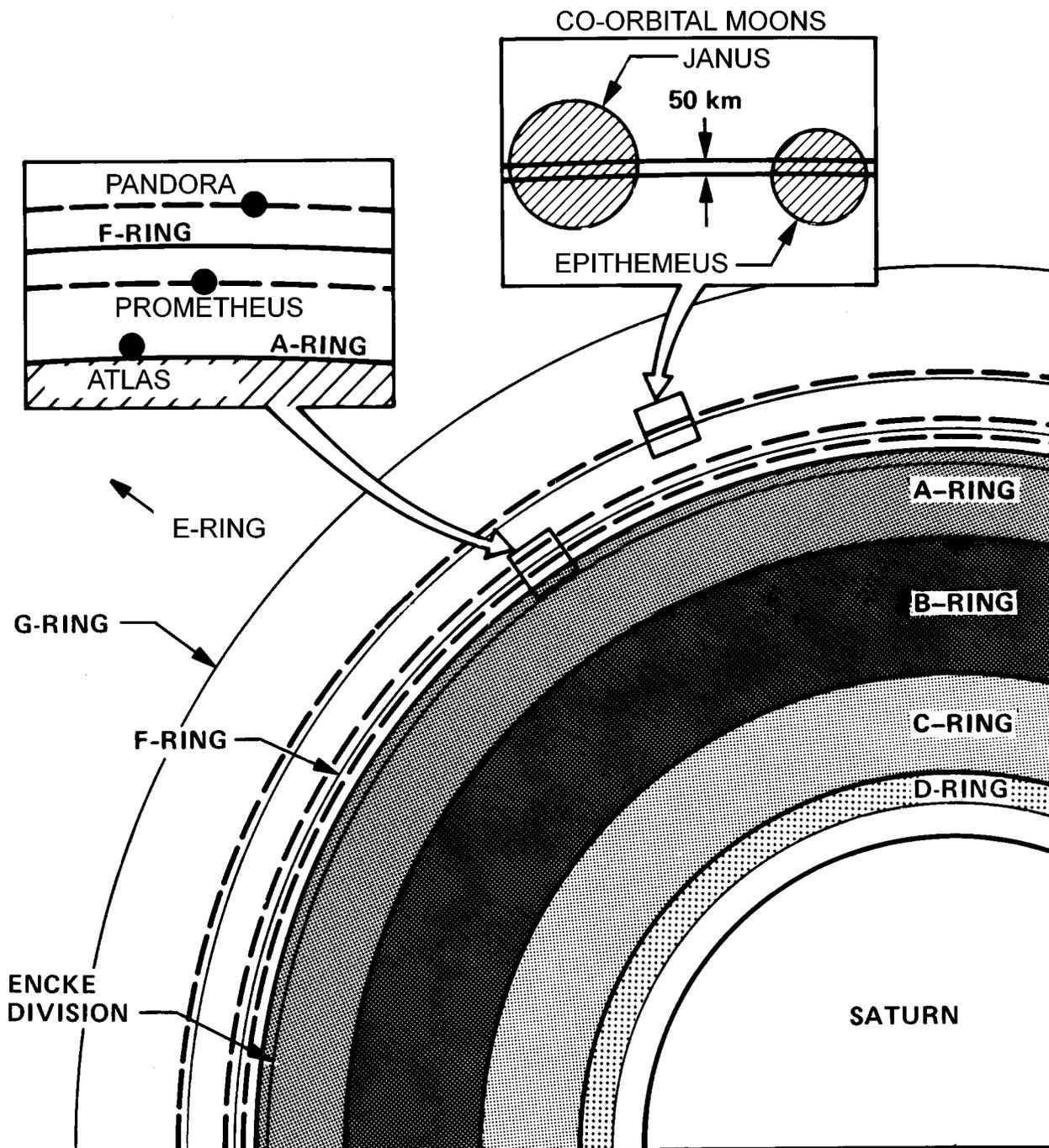


*Model of Titan's atmosphere*

form a dense core, covered by a mantle of water, ammonia and methane ices.

The mixture of ammonia with water could ensure that Titan's interior is still partially unsolidified, as the ammonia would effectively act like antifreeze. Radioactive decay in the rocky material in the core could heat the core and mantle, making it possible that a liquid layer could exist today in Titan's mantle.

Methane could be trapped in Titan's water ice crust, which could provide a possible long term source for the methane in Titan's atmosphere if it were freed by ongoing volcanic processes. Due to Titan's thick natural smog, Voyager was prevented from viewing the surface; the images showed a featureless orange face. Spectroscopic observations by Voyager's infrared spectrometer revealed traces of ethane, propane, acetylene and other organic molecules in addition to methane. These hydrocarbons are produced by the combination of solar ultraviolet light and electrons from Saturn's rapidly rotating magnetosphere striking Titan's atmosphere. Hydrocarbons produced in the atmosphere eventually condense out and rain down on the surface, thus there may exist lakes of ethane and methane, perhaps enclosed in the round bowls of impact craters. Titan's hidden surface may have exotic features such as mountains sculpted by



*Saturn's rings*

hydrocarbon rain, and perhaps rivers, lakes and "waterfalls" of exotic liquids. Water and ammonia magma from Titan's interior may occasionally erupt, spreading across the surface.

Titan's orbit takes it both inside and outside the magnetosphere of Saturn. When Titan is outside the magnetosphere and exposed to the solar wind, its interaction may be similar to that of other bodies in the solar system such as Mars, Venus or comets (these bodies have substantial interaction with the solar wind, and, like Titan, have atmospheres but no strong internal

magnetic fields).

The interaction of Titan with the magnetosphere provides a way for both the magnetospheric plasma to enter Titan's atmosphere and for atmospheric particles to escape Titan. Voyager results suggested that this interaction produces a torus of neutral particles encircling Saturn, making Titan a potentially important source of plasma to Saturn's magnetosphere. The characteristics of this torus are yet to be explored, and will be studied by the Cassini orbiter. The interaction of ice particles and dust from Saturn's rings will play a special role as the dust moves out towards Titan's torus and becomes charged by collisions. When the dust is charged it behaves partially like a neutral particle orbiting Titan according to Kepler's laws (gravity driven), and partially like a charged particle moving with Saturn's magnetosphere. The interaction of dust with Saturn's magnetosphere will provide scientists with a detailed look at how dust and plasma interact.

Electrical storms and lightning may exist in Titan's skies. Cassini will search for visible lightning and listen for "whistler" emissions that can be detected when lightning discharges a broad band of electromagnetic emission, part of which can propagate along Saturn's magnetic field lines. These emissions have a decreasing tone with time (because the high frequencies arrive before the low frequencies). Lightning whistlers have been detected in both Earth's and Jupiter's magnetosphere. They can be detected by radio and plasma-wave instruments from large distances and also can be used to estimate the frequency of lightning.

Titan may have its own internally generated magnetic field. Recent results from the Galileo spacecraft at Jupiter indicate the possibility of an internally generated magnetic field associated with the moon Ganymede. For Titan there are two possibilities: A magnetic field could be induced from the interaction of Titan's substantial atmosphere with the flow of Saturn's magnetosphere (like Venus's interaction with the solar wind); or a magnetic field could be generated internally from dynamo action in a metallic molten core (like Earth's). (Under the dynamo theory, a magnetic field is created by the circling motion of electrically charged material in the core.) In addition to being important to understanding the Titan interaction with Saturn's magnetosphere, a Titan magnetic field, if generated internally, would help scientists define the natural satellite's interior structure.

## **The Rings**

From a distance, the rings of Saturn look like majestically symmetrical hoops surrounding the planet. Up close, however, from the views provided by the Voyager spacecraft, the rings turn out to be a still splendid but somewhat unruly population of ice and rock particles jostling against each other or being pushed and pulled into uneven orbits by bigger particles and by Saturn's many moons.

The mass of all the ring particles measured together would comprise a moon about the size of Mimas, one of Saturn's medium-small moons. The rings may, in fact, be at least partly composed of the remnants of such a moon or moons, torn up by gravitational forces.

Their precise origin is a mystery. It is not known if rings formed around Saturn out of the initial solar system nebula, or after one or more moons were torn apart by Saturn's gravity. If the rings were the result of the numerous comets captured and destroyed by Saturn's gravity, why are Saturn's bright rings so different in nature from the dark rings of neighboring planets? Over the lifetime of the rings, they must have been bombarded continually by comets and meteors — and therefore they should have accumulated a great amount of carbonaceous and silicate debris — yet water ice is the only material positively identified in spectra of the rings.

The effects of torque and gravitational drag — along with the loss of momentum through collisions — should have produced a system only one-tenth to one-hundredth the age of the solar system itself. If this hypothesis is correct, then we cannot now be observing a ring system around Saturn that formed when the solar system formed.

In fact, Saturn's rings — as well as the rings of all the other large planets — may have formed and dissipated many times since the beginning of the solar system. An extraordinarily complex structure is seen across the entire span of Saturn's ring system. The broad B-ring, for instance, often contains numerous "spokes" — radial, rotating features that may be caused by a combination of magnetic and electrostatic forces. The individual rings themselves defy definition; the count in high-resolution images suggests anywhere from 500 to 1,000 separate rings. Named in order of discovery, the labels that scientists have assigned to the major rings do not indicate their relative positions. From the planet outward, they are known as the D-, C-, B-, A-, F-, G- and E-rings.

The possibility of numerous, small natural satellites within Saturn's ring system was a puzzle the Voyager mission had hoped to solve. Voyager's best-resolution studies of the ring system were aimed at revealing any bodies larger than about 10 kilometers (about 6 miles) in diameter; but only three were found and none were located within the main ring complex.

The Voyager high-resolution studies did, however, detect signs of small moonlets not actually resolved in the images. When a small, dense body passes near a section of low-density ring material, its gravitational pull distorts the ring and creates what are known as "edge waves."

Cassini will be able to perform a number of the experiments that Voyager used to detect other gravitational effects on Saturn's ring material. One experiment involves "watching" as a beam of light (or, in one case, radio waves) passes through the ring, then observing the effects of the ring material on the beam. As the beam passes through the ring material, it may be attenuated or even extinguished. This "occultation" experiment provides an extremely high-resolution study of a single path across the rings — with resolutions up to about 100 meters (about 330 feet), Cassini will obtain far more detailed information on ring structures than the Voyager instruments.

Voyager's instruments did detect many minute ring structures and found that the F-ring was far more complex than images had suggested. The data set, furthermore, showed that the B-ring was quite opaque in regions, and the Cassini "division" was not at all empty. It also pro-

vided a direct measurement of the maximum thickness of the ring system in several locations, finding it to be much less than 100 meters (about 330 feet) thick there.

Many narrow ringlets were found with slightly eccentric, non-circular shapes and orbits. These eccentric ringlets generally lie in gaps in the mass of nearly circular rings that make up the majority of Saturn's ring system. Voyager also found very few truly empty "gaps" in the ring system. Moonlets inside the rings do appear to clear lanes within the ring plane, giving the rings their grooved appearance.

Voyager cameras found shepherd moons that tend to contain ring particles that would otherwise spread. Also seen were density waves that move through portions of the ring plane like a crowd starting a "wave" in a stadium. This phenomenon is due to the effects of one or more moons or moonlets gravitationally tugging on ring particles.

Gravitational interactions with moons seem to create most of the structure visible in the rings, but some structural detail exists even where there is no gravitational interaction with a moon. Some poorly understood fluid physics may be responsible for some unexplained structure in the rings. Other ring features may be explained by moonlets or large particles in the rings that have gone undetected.

Voyager images showed dark, radial structures on the rings. These so-called "spokes" were seen as they formed and rotated about the planet. Spokes seemed to appear rapidly — as a section of ring rotated out of the darkness near the dawn terminator — and then dissipate gradually, rotating around toward the dusk terminator of the ring. A spoke's formation time seemed to be very short; in some imaging studies they were seen to grow more than 6,000 kilometers (about 3,700 miles) in distance in just 5 minutes.

The spokes in Saturn's rings have an unexplained link with the planet's magnetic field, and are likely just one visible manifestation of many interactions the rings have with Saturn's electromagnetic fields.

Ground-based infrared studies of the spectra of the A- and B-rings show that they are composed largely, perhaps even exclusively, of water ice. The spectral characteristics of the rings are also very similar to those of several of Saturn's inner moons.

Studies of the main rings show that the ring system is not completely uniform in its makeup, and that some sorting of materials within the A- and B-rings exists. Why such a non-uniform composition exists is unknown. The E-ring is somewhat bluish in color — and thus different in makeup from the main rings. It is believed that the moon Enceladus is the source of E-ring material.

Since ring particles larger than about 1 millimeter represent a considerable hazard to the Cassini spacecraft, the mission plan will include efforts to avoid dense particle areas of Saturn's ring plane. The spacecraft will be oriented to provide maximum protection for itself and its sen-

sitive instrumentation packages. Even with such protective measures, passage through the ring plane out beyond the main rings will allow Cassini's instruments to make important measurements of the particles making up the less dense regions of the Cassini ring plane. These studies could provide considerable insight into the composition and environment of the ring system and Saturn's icy natural satellites.

## **The Icy Moons**

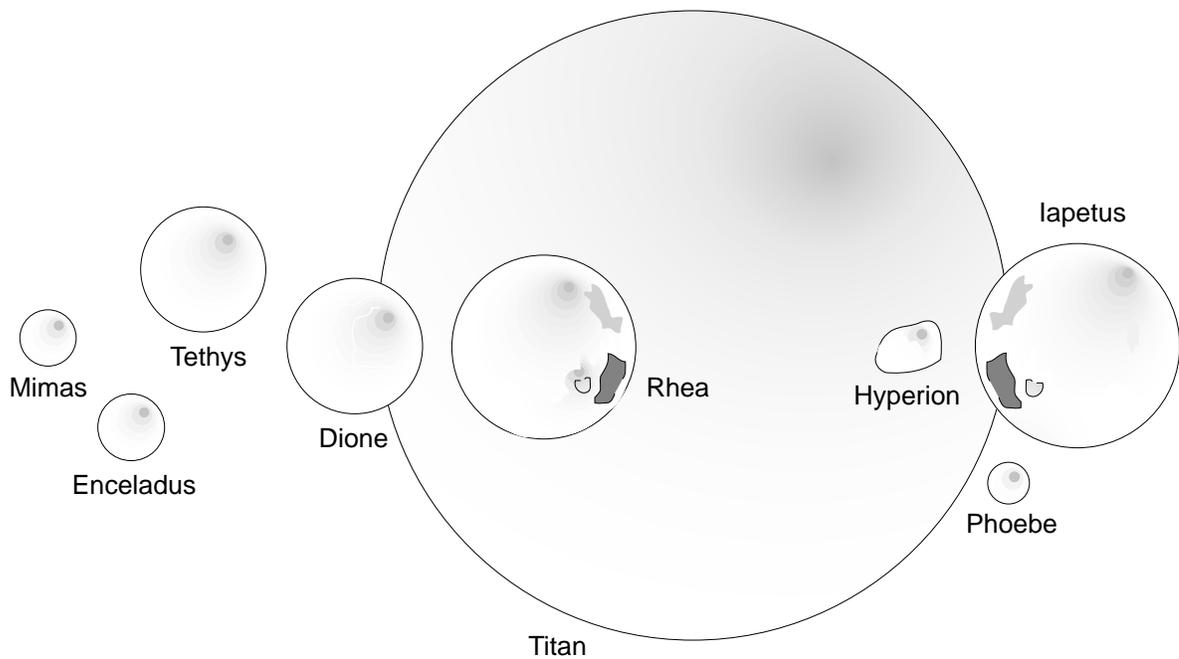
The moons of Saturn are diverse — ranging from the planet-like Titan to tiny, irregular objects only tens of kilometers (or miles) in diameter. These bodies are all (except perhaps Phoebe) believed to hold not only water ice, but also other components such as methane, ammonia and carbon dioxide. Saturn has at least 18 moons; there are likely other small, undiscovered natural satellites in the planet's system.

Many of the smallest moons were discovered during the Voyager spacecraft flybys. The 18th moon, Pan, was found nearly 10 years after the flybys during close analysis of Voyager images; it is embedded in the Encke Gap within Saturn's A-ring. Saturn's ring plane crossings — when the obscuring light from Saturn's bright rings dims as the rings move to an edge-on orientation from Earth's perspective — represent the ideal time for discovering new moons. Images obtained by the Hubble Space Telescope during the ring plane crossings in 1995 and 1996, however, did not reveal any unambiguous discoveries of new moons.

Before the advent of spacecraft exploration, scientists expected the moons of the outer planets to be geologically dead. They assumed that heat sources were not sufficient to have melted the moons' mantles enough to provide a source of liquid, or even semi-liquid, ice or ice silicate slurries. The Voyager and Galileo spacecraft have radically altered this view by revealing a wide range of geological processes on the moons of the outer planets. For example, Saturn's moon Enceladus may be currently active. Several of Saturn's medium-sized moons are large enough to have undergone internal melting with subsequent differentiation and resurfacing.

Many moons in the outer solar system show the effects of tidal interactions with their parent planets, and sometimes with other moons. This gravitational pushing and pulling can heat a moon's interior, causing tectonic, volcanic or geyser-like phenomena. Another factor is the presence of non-ice components, such as ammonia hydrate or methanol, which lower the melting point of near-surface materials. Partial melts of water ice and various other components — each with their own melting point and viscosity — provide material for a wide range of geological activity.

Because the surfaces of so many moons of the outer planets exhibit evidence of geological activity, planetary scientists have begun to think in terms of unified geological processes occurring on the planets and their moons. For example, partial melts of water ice with other materials could produce flows of liquid or partially molten slurries similar to lava flows on Earth that result from the partial melting of silicate rock mixtures. The ridged and grooved ter-



*Saturn's major moons*

rains on moons such as Saturn's Enceladus and Tethys may have resulted from tectonic activities found to occur throughout the solar system. The explosive volcanic eruptions possibly occurring on Enceladus may be similar to those occurring on Earth.

Several of Saturn's moons underwent periods of melting and active geology within a billion years of their formation and then became quiescent. For nearly a billion years after their formation, the moons all underwent intense bombardment and cratering. The bombardment tapered off to a slower rate, but still continues. By counting the number of craters on a moon's surface, and making certain assumptions about the amount and frequency of impacting material, geologists are able to estimate when a specific portion of a moon's surface was formed.

Meteorites bombarding icy bodies change the surfaces by excavating and exposing fresh material. Impacts can also cause some surface or subsurface materials to turn to vapor, and the subsequent escape of those vaporized materials can create a slag deposit enriched in opaque, dark materials. Both the moons of Jupiter and the medium-sized moons of Saturn tend to be brighter on the hemispheres leading in the direction of orbital motion (each moon's so-called "leading" side, as opposed to its "trailing" side); this effect is thought to be due to the roughing-up and coating that the leading side receives from meteor bombardment.

Saturn's six largest moons after Titan are smaller than Titan and Jupiter's giant Galilean moons, but they are still sizable and represent a unique class of icy satellite. Tethys, Rhea, Iapetus, Mimas and Enceladus are thought to be largely water ice, possibly mixed with ammonia or other volatiles. They have smaller amounts of rocky silicates than the Galilean moons.

❑ Saturn's innermost, medium-sized moon, **Mimas**, is covered with craters, including one named Herschel that covers a third of the moon's diameter. There is a suggestion of grooves in its surface that may be features caused by the impact that created Herschel. The craters on Mimas tend to be high-rimmed, bowl-shaped pits. Crater count of Mimas suggest that it has undergone several episodes of resurfacing.

❑ The next moon outward from Saturn is **Enceladus**, an object that was known from telescope measurements to reflect nearly 100 percent of the visible light it receives. This leads scientists to believe Enceladus' surface is probably pure water ice. Voyager 2 images reveal a surface that had been subjected in the recent geological past to extensive resurfacing. Grooved formations similar to those on the Galilean moon Ganymede are prominent.

The lack of impact craters on part of Enceladus leads scientists to conclude the age of its surface is less than a billion years. Some form of ice volcanism may be currently occurring on Enceladus. One possible source of heating is tidal interactions, perhaps with the moon Dione.

Enceladus is possibly responsible for the formation of Saturn's E-ring. This ring is a tenuous collection of icy particles that extends from inside the orbit of Enceladus to beyond the orbit of Dione, but is much much thicker than Saturn's other rings. The maximum thickness position of the ring coincides with the orbital position of Enceladus. If some form of volcanism is occurring on the surface, it could provide a source of particles for the ring.

❑ **Tethys** is covered with impact craters, including Odysseus, an enormous impact structure more than 400 kilometers (250 miles) in diameter, or more than one-third of the moon's diameter of 1,060 kilometers (658 miles). The craters tend to be flatter than those on Mimas or Earth's Moon, probably because they have been smoothed out over the eons under Tethys' stronger gravitational field. Evidence for episodes of resurfacing is seen in regions that have fewer craters and higher reflectivity. In addition, there is a huge trench formation, the Ithaca Chasma, which may be a degraded form of the grooves found on Enceladus.

❑ **Dione** is about the same size as Tethys but more dense, and shows a wide variety of surface features. Next to Enceladus among Saturn's moons, it has the most extensive evidence for internal activity. It has enough rocky material in its makeup to produce heat from natural radioactivity, which could be the cause of its internal activity. Most of the surface is heavily cratered, but gradations in crater density indicate that several periods of resurfacing occurred during the first billion years of Dione's existence. The leading side of the moon is about 25 percent brighter than the other, due possibly to more intensive bombardment by micrometeorites on the darker hemisphere. Wispy streaks, which are about 50 percent brighter than the surrounding areas, are believed to be the result of internal activity and subsequent flows of erupting material.

❑ **Rhea** appears to be superficially very similar to Dione. Bright, wispy streaks cover one hemisphere. No resurfacing events seem to have occurred in its early history, however. Some regions lack large craters, while other regions have a preponderance of such impacts. The

larger craters may be due to a population of larger debris that was more prevalent during an earlier era of collisions.

□ When the astronomer Cassini discovered **Iapetus** in 1672, he noticed almost immediately that at one point in its orbit around Saturn it was very bright, but on the opposite side of the orbit, the moon nearly disappeared. He correctly deduced that the trailing hemisphere is composed of highly reflective material, while the leading hemisphere is strikingly darker. (This sets Iapetus apart from Saturn's other moons and the moons of Jupiter, which tend to be brighter on their leading hemispheres.) Voyager images show that the bright side, which reflects nearly 50 percent of the light it receives, is fairly typical of a heavily cratered icy satellite. The other side, which is the face that Iapetus puts forth as it moves forward in its orbit, is coated with a much darker, redder material that has a reflectivity of only about 3 to 4 percent.

Scientists still do not agree on whether the dark material originated from an outside source or was created from Iapetus' own interior. One scenario for the outside deposit of material would involve dark particles being ejected from the little moon Phoebe and drifting inward to coat Iapetus. The major problem with this model is that the dark material on Iapetus is redder than Phoebe, although the material could have undergone chemical changes after its expulsion from Phoebe that made it redder. One observation lending credence to an internal origin is the concentration of material on crater floors, which implies that something is filling in the craters. In one model proposed by scientists, methane could erupt from the interior and then become darkened by ultraviolet radiation.

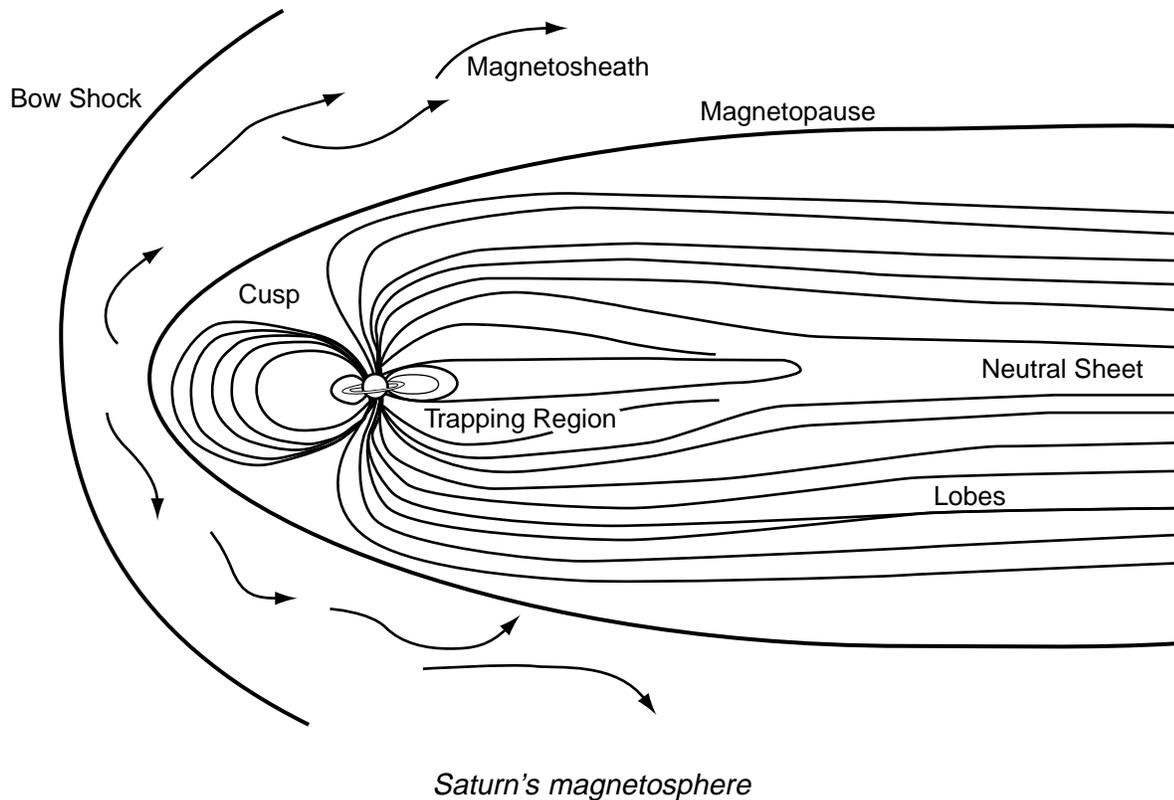
Iapetus is odd in other respects. It is the only large Saturn moon in a highly inclined orbit, one that takes it far above and below the plane in which the rings and most of the moons orbit. It is less dense than objects of similar brightness, which implies that it has a higher fraction of ice or possibly methane or ammonia in its interior.

## **Small Moons**

The Saturn system has a number of unique, small moons. Two types of objects have been found only in Saturn's system: the co-orbital moons and the Lagrangians. A third type of object, shepherding moons, have been found only at Saturn and Uranus. All three groups of moons are irregularly shaped and probably consist primarily of ice.

Three shepherds — Atlas, Pandora and Prometheus — are believed to play a key role in defining the edges of Saturn's A- and F-rings. The orbit of Atlas lies several hundred kilometers (or miles) from the outer edge of the A-ring. Pandora and Prometheus, which orbit on either side of the F-ring, constrain the width of this narrow ring and may cause its kinky appearance.

The co-orbital moons Janus and Epimetheus, discovered in 1966 and 1978, respectively, exist in an unusual dynamic situation. They move in almost identical orbits. Every four years, the inner moon (which orbits slightly faster than the outer one) overtakes its companion. Instead of colliding, the moons exchange orbits. The four-year cycle then begins again. Perhaps these two moons were once part of a larger body that disintegrated after a major collision.



The three other small moons of Saturn — Calypso, Helene and Telesto — orbit in the Lagrangian points of larger moons, one associated with Dione and two with Tethys. The Lagrangian points are locations within an object's orbit in which a less massive body can move in an identical, stable orbit. The points lie about 60 degrees in front of and behind the larger body. (Although no other known moons in the solar system are Lagrangians, the Trojan asteroids orbit in two of the Lagrangian points of Jupiter. Mars also has an asteroid at one Lagrangian point.)

Telescope observations showed that the surface of Hyperion, which lies between the orbits of Iapetus and Titan, is covered with ice. Because Hyperion is not very reflective, its ice must be mixed with a significant amount of darker, rocky material. The color of Hyperion is similar to that of the dark side of Iapetus and D-type asteroids: all three bodies may be rich in primitive material rich in organic compounds. Although Hyperion is only slightly smaller than Mimas, it has a highly irregular shape which, along with a battered appearance, suggests that it has been subjected to intense bombardment and fragmentation. There is also evidence that Hyperion is in a chaotic rotation — probably the result of tidal forces during close passages of nearby Titan.

Saturn's outermost moon, Phoebe, a dark object with a surface composition probably similar to that of C-type asteroids, is in a wrong-way orbit compared to the other moons (this is called a "retrograde" orbit). The orbit is also highly inclined, taking Phoebe high above and below the plane on which the rings and most of the moons orbit. These peculiar orbital charac-

teristics alone suggest that Phoebe may be a captured asteroid. Voyager images show a mottled appearance. Although it is smaller than Hyperion, Phoebe has a nearly spherical shape.

Pan, the 18th known moon of Saturn, was discovered in 1990 in Voyager 2 images that were taken in 1981. This small object is embedded within the A-ring and helps to clear the particles out of the Encke division.

## **The Magnetosphere**

Saturn, its moons and rings sit inside an enormous bubble in the solar wind created by the planet's strong magnetic field. This "sphere of influence" of Saturn's magnetic field — called a magnetosphere — resembles a similar, but smaller, magnetic bubble surrounding Earth. The same kind of structure envelopes Jupiter and several other bodies in the solar system. A supersonic "solar wind" of electrically charged particles blows outward from the Sun within our star's own magnetosphere. The pressure of this solar wind against a planet's magnetosphere compresses the sunward side of the sphere and blows past the planet, giving the magnetosphere a drawn-out shape like that of a comet.

Inside Saturn's vast magnetospheric bubble is a mixture of particles including electrons, various species of ions and neutral atoms and molecules, several populations of very energetic charged particles (like those in Earth's Van Allen Belts) and charged dust grains. The charged particles and dust grains all interact with both the steady and the fluctuating electric and magnetic fields present throughout the magnetosphere.

The primary sources of particles in Saturn's magnetosphere are thought to be the moons Dione and Tethys, which are bombarded by the more energetic particles. But the solar wind, ionosphere, rings, Saturn's atmosphere, Titan's atmosphere and the other icy moons are sources as well.

The mysterious "spokes" in the rings of Saturn are probably caused by electrodynamic interactions between the tiny charged dust particles in the rings and the magnetosphere. Auroras, which exist on Saturn as well as Earth, are produced when trapped charged particles spiral down along magnetic field lines leading to the planet and collide with gases in the atmosphere. Scientists generally agree that the internal magnetic fields of the giant planets arise from an electrical field generated somewhere inside the planets' liquid interiors. Saturn's interior is probably quite exotic because of the great pressures caused by its large size. There may be a molten rocky core, but wrapped around this core scientists would expect to find layers of uncommon materials such as liquid metallic hydrogen and perhaps liquid helium.

Making measurements close to the planet over a wide range of latitudes and longitudes, Cassini will measure the details of the gravitational and magnetic field and tell us more about Saturn's interior. The spacecraft's magnetometer will measure the strength and direction of the magnetic field throughout the magnetosphere — close to the planet where the field is nearly dipolar, and further from the planet where electrical currents create a non-dipolar field. The magnetometer will measure the planet's magnetic field with sufficient accuracy to determine if

it is indeed symmetrical. If so, the basic tenets of the dynamo theory invented to explain planetary magnetic fields may need to be reexamined.

Among all the planets with magnetic fields, there are two main sources of energy driving magnetospheric processes: the planet's rotation and the solar wind. In turn there are two types of large-scale plasma flow within the magnetosphere — co-rotation and convection. The nature of the large-scale circulation of particles in the magnetosphere depends on which source is dominant. At Earth, the energy is derived primarily from the solar wind; at Jupiter it is derived from the planet's rapid rotation rate. Saturn's magnetosphere is especially interesting because it is somewhere in between; both energy sources should play an important role.

The rotation of Saturn's magnetic field with the planet creates a large electric field that extends into the magnetosphere. The combination of this electric field and Saturn's magnetic field create electromagnetic forces that cause charged plasma particles to "co-rotate" (rotate together with Saturn and its internal magnetic field) as far out as Rhea's orbit.

The other large-scale flow of charged particles, convection, is caused by the solar wind pulling the lines of the magnetic field toward the tail of the magnetosphere. This leads to a plasma flow from dayside to nightside on open field lines, as well as a return flow from nightside to dayside on closed field lines (particularly near the equatorial plane).

Saturn has an ionosphere, a thin layer of partially ionized gas at the top of the sunlit atmosphere. Collisions between particles in the atmosphere and the ionosphere create a frictional drag that causes the ionosphere to rotate together with Saturn and its atmosphere.

# Mission Overview

The Cassini mission will span 11 years, including 6-1/2 years of interplanetary cruise and four years in orbit at Saturn. Along the way the spacecraft will fly by several planets, making use of their gravitational energy to speed its flight toward Saturn.

## Launch

**Launch periods.** Given the relative positions of the planets and the trajectory Cassini must fly, the primary launch period opens on October 6, 1997, and continues through November 15. Launch is scheduled for October 13, 1997.

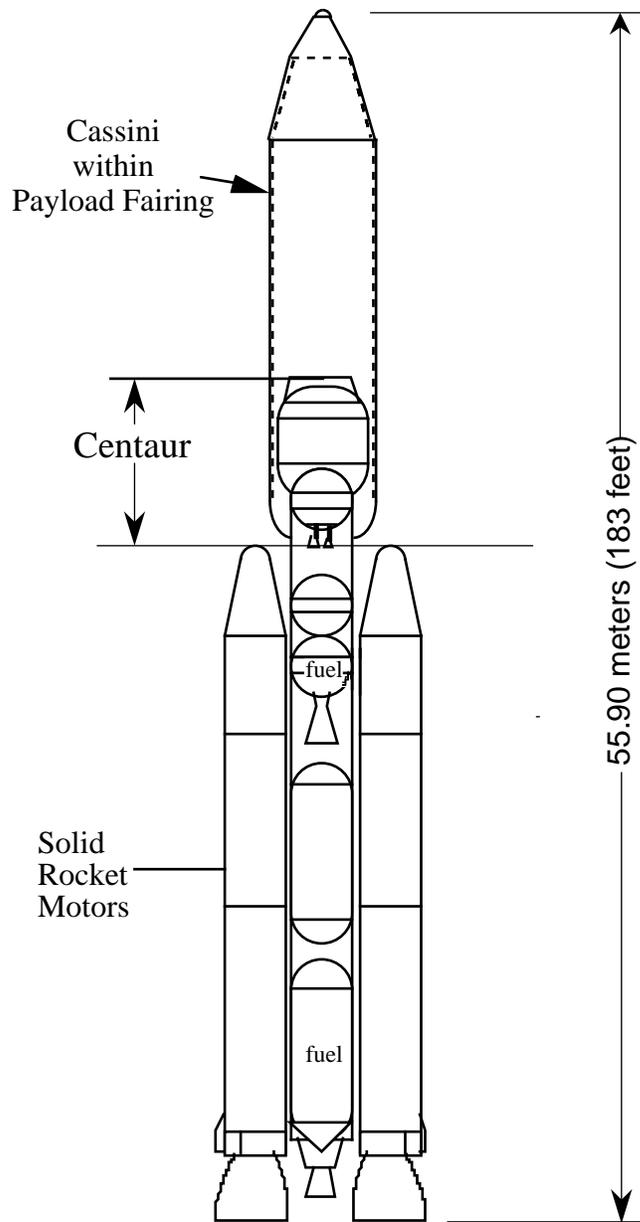
The best conditions exist from October 6 through November 4; launching between those dates would result in Cassini arriving at Saturn in July 2004. The period from November 5 to 15 is considered a contingency period; Cassini's launch is still feasible but less desirable, as more spacecraft propellant would be needed to refine its flight path and the arrival at Saturn would be delayed by many months. A launch from November 5 through 9 would place the spacecraft at Saturn in December 2004; launching from November 10 through 13, Cassini would arrive at Saturn in July 2005. Launching on November 14 or 15 would deliver the spacecraft to Saturn in December 2005.

Secondary and backup trajectories exist in the unplanned event that Cassini is not launched during the primary launch period. Both require the spacecraft to fly a Venus-Earth-Earth gravity assist (VEEGA) trajectory instead of the Venus-Venus-Earth-Jupiter (VVEJGA) trajectory required for the primary launch period.

The secondary launch period is a 45-day period between November 28, 1997, and January 11, 1998. The spacecraft's arrival at Saturn would be October 13, 2006, after a flight of 8.8 years. The significant difference between this mission and the primary one is a longer interplanetary cruise and poorer illumination of Saturn's rings due to their changing angle relative to the Sun and Earth.

There is also a backup launch period from March 19 through April 5, 1999, requiring a flight of 9.8 years to Saturn with an arrival date of December 22, 2008. This mission entails a much longer flight time to Saturn. Studies of Saturn's rings would be significantly degraded due to the angle of the rings. Due to the long flight time, electrical power output from the radioisotope thermoelectric generators would be degraded. This would result in fewer instruments being allowed to operate at a given time, or in lower power states, or with less engineering support for a suite of instruments.

**Daily window.** The launch window on October 13 opens at 4:55 a.m. Eastern Daylight Time and extends for 140 minutes. After that date, the opening time of the launch window moves earlier by about six minutes daily. The length of the window on subsequent days remains at 140 minutes per day.

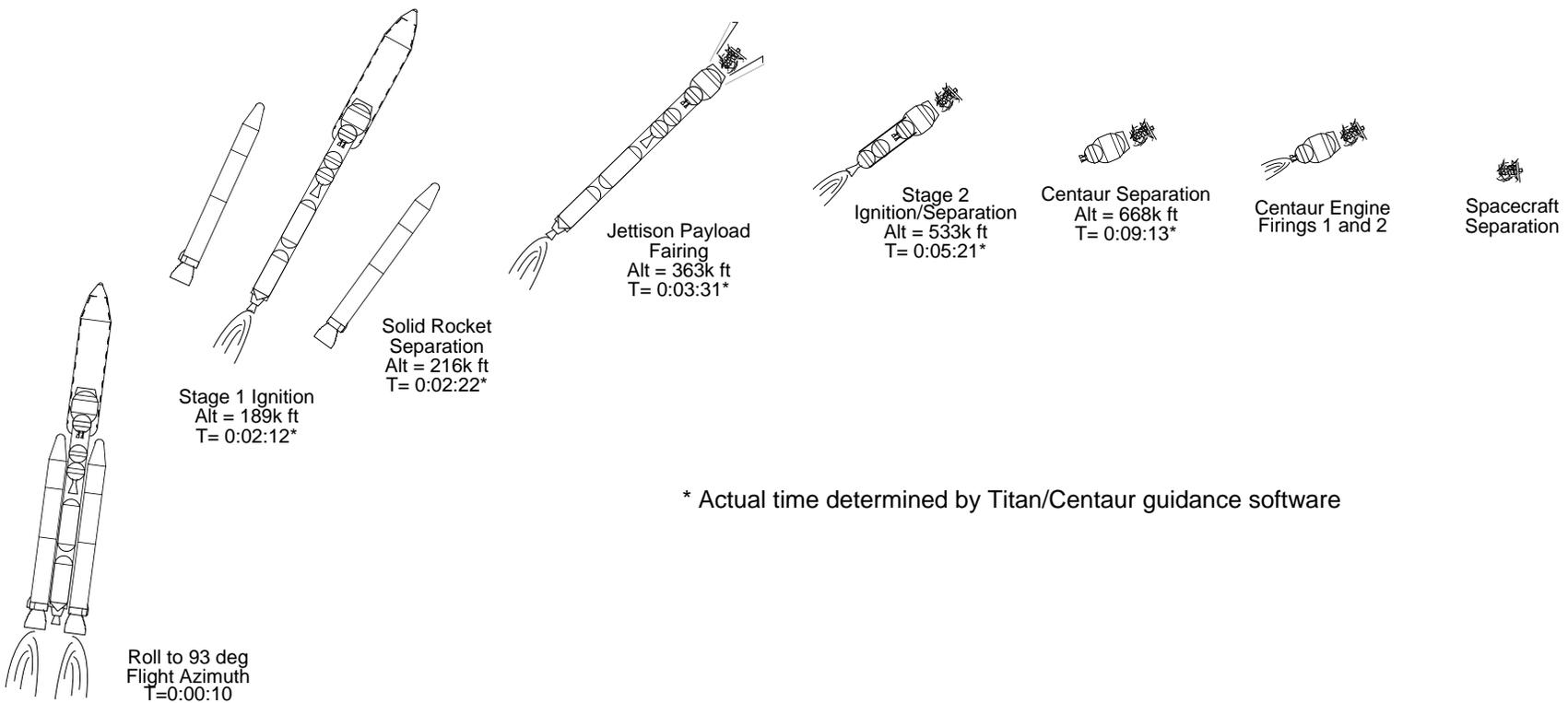


*Cassini's Titan IVB launch vehicle*

## Launch Vehicle

The Titan IVB launch vehicle consists of two upgraded solid rocket motors (known as SRMUs); a two-stage liquid-propellant core; a liquid-fuel upper stage; and a payload fairing.

The three-segment SRMUs are 3.2 meters (10.5 feet) in diameter and 34.2 meters (112.4 feet) long. Each motor contains 312,458 kilograms (688,853 pounds) of hydroxyl terminated polybutadiene (HTPB) propellant and provides a maximum thrust of 7.56 million newtons (1.7 million pounds) at sea level. Flight control is achieved by directing the thrust through a gim-



\* Actual time determined by Titan/Centaur guidance software

Launch events

baled nozzle controlled by hydraulic actuators. Six staging rockets on each SRMU ensure positive separation from the core following SRMU burnout.

The first stage of the 3.04-meter-diameter (10-foot) core is powered by a twin assembly LR87-AJ-11 engine, while the second stage is powered by a single assembly LR91-AJ-11 engine. Both stages use storable hypergolic propellants (propellants that ignite when they come in contact with each other). The fuel is aerzine 50, a 50-50 mixture of hydrazine and unsymmetrical dimethyl hydrazine. During combustion, the fuel is mixed with nitrogen tetroxide as an oxidizer.

Vehicle flight control and navigation for the Titan are provided by the guidance control unit, which includes a flight control subsystem and an inertial measurement subsystem. The first stage separates from the second stage when the second-stage engine ignites. Separation of the second stage and the Centaur upper stage is achieved when four retrorockets fire and a structural adapter is severed by pyrotechnics called "SuperZip."

The payload fairing is 5.9 meters (16.7 feet) in diameter, 20 meters (66 feet) long and has an aluminum structure.

**Centaur upper stage.** The Centaur upper stage, managed by NASA's Lewis Research Center and produced by Lockheed Martin Astronautics, is 8.9 meters (29.45 feet ) long and 4 meters (14 feet) in diameter. It provides 147,000 newtons (33,000 pounds) of engine thrust using cryogenic liquid oxygen and liquid hydrogen.

## **Launch Events**

Variations in launch date have minimal impact on the launch sequence of events through and including the first firing of the Centaur upper stage. A launch slip would shift the entire sequence equally. But the sequence of events following the first Centaur firing — including the coast period in parking orbit and the Centaur's second firing — would depend on the launch slip.

Launch begins with the ignition of the solid rocket motors, which burn for 2 minutes, 22 seconds to an altitude of approximately 66,000 meters (216,500 feet). The first stage of the liquid-fueled Titan ignites at 2 minutes, 12 seconds into flight at an altitude of about 58,000 meters (189,000 feet).

At an altitude of approximately 110,600 meters (363,000 feet) and 3 minutes, 31 seconds into flight, the payload fairing that surrounds the spacecraft is jettisoned. Ignition of the Titan's second stage occurs at 5 minutes, 21 seconds into flight at an altitude of approximately 162,500 meters (533,000 feet). At approximately 9 minutes, 13 seconds into flight at an altitude of about 203,600 meters (668,000 feet), the Centaur upper stage and the Cassini spacecraft separate from the Titan. (The exact time of separation — and the actual start times, burn durations and separation of the Centaur from Cassini — are determined by Titan/Centaur guidance software.)

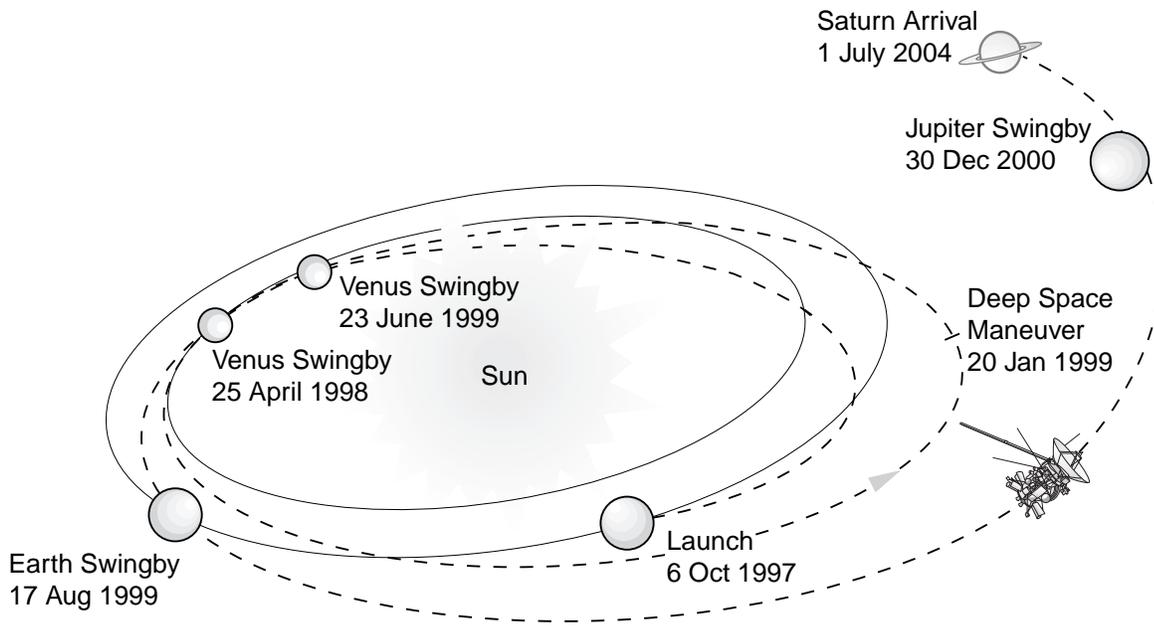
At Titan-Centaur separation, flight control is transferred to the Centaur. Following separation, the Centaur completes a pre-burn sequence and is ignited for the first of two burns in what is referred to as main engine start #1. The burn ends after 131 seconds at main engine cutoff #1. After some settling time, the spacecraft and Centaur are injected into a parking orbit with a perigee (closest point to Earth) of 170 kilometers (105 miles) perigee and an apogee (farthest point from Earth) of 445 kilometers (276 miles), with an orbital inclination between 28.6 and 31.6 degrees, depending on the time of launch. This parking orbit is designed to provide an orbital lifetime of about 20 days in case the Centaur fails to restart its main engine successfully. The Centaur/spacecraft combination will coast in parking orbit until trajectory conditions are right for interplanetary injection. The coast time in parking orbit between the first main engine cutoff and the engine restart will be 8 to 32 minutes if launch takes place in the primary period, depending on the time and day liftoff occurs. The coast duration is about 14 minutes for an October 6 launch date at the opening of the daily window.

Toward the end of this coast period, the Centaur is oriented for its second burn using thrusters. After the Centaur engine is restarted, it will burn for approximately 7 to 8 minutes. Some 30 seconds after the conclusion of this second burn, the Centaur issues a command instructing the Cassini spacecraft to prepare for separation from the Centaur. By five minutes after the second Centaur engine cutoff, the Centaur orients Cassini's high-gain antenna to point toward the Sun and begins to roll to the separation attitude. This maneuver is completed by 6 minutes after the second engine cutoff. Six minutes after the second engine cutoff, the Cassini spacecraft receives a command instructing it to fire explosive devices separating it from the Centaur. Final separation is completed by 6-1/2 minutes after the second Centaur engine cutoff.

### **Post-Separation Events**

After separating from the Centaur, Cassini's attitude control and articulation subsystem gains control over the spacecraft and ensures that the high-gain antenna is pointed toward the Sun to keep the rest of the spacecraft shaded. The onboard computer then places the spacecraft in a "safe" state so that it could operate autonomously for up to 10 days in the event of telecommunications problems. The Canberra, Australia, complex of NASA's Deep Space Network will be the first to acquire Cassini's signal.

The Centaur executes a collision and contamination avoidance maneuver that prevents it from impacting either Venus or the spacecraft. This burn occurs approximately 20 minutes after separation to allow the Cassini spacecraft and the Centaur to drift apart, insuring that the plume from the Centaur's reaction control thrusters does not impact the spacecraft. About eight minutes later, the Centaur executes a "blowdown" maneuver to expel unused propellant and to further reduce the probability of impact with Cassini or Venus. About an hour after separation, the Centaur depletes the hydrazine from its reaction control subsystem. The Centaur mission ends approximately 87 minutes after separation. By this time, Cassini has its high-gain antenna pointed toward the Sun, is transmitting real-time telemetry via one of its two low-gain antennas, and is awaiting instructions from the ground.



*Interplanetary Trajectory*

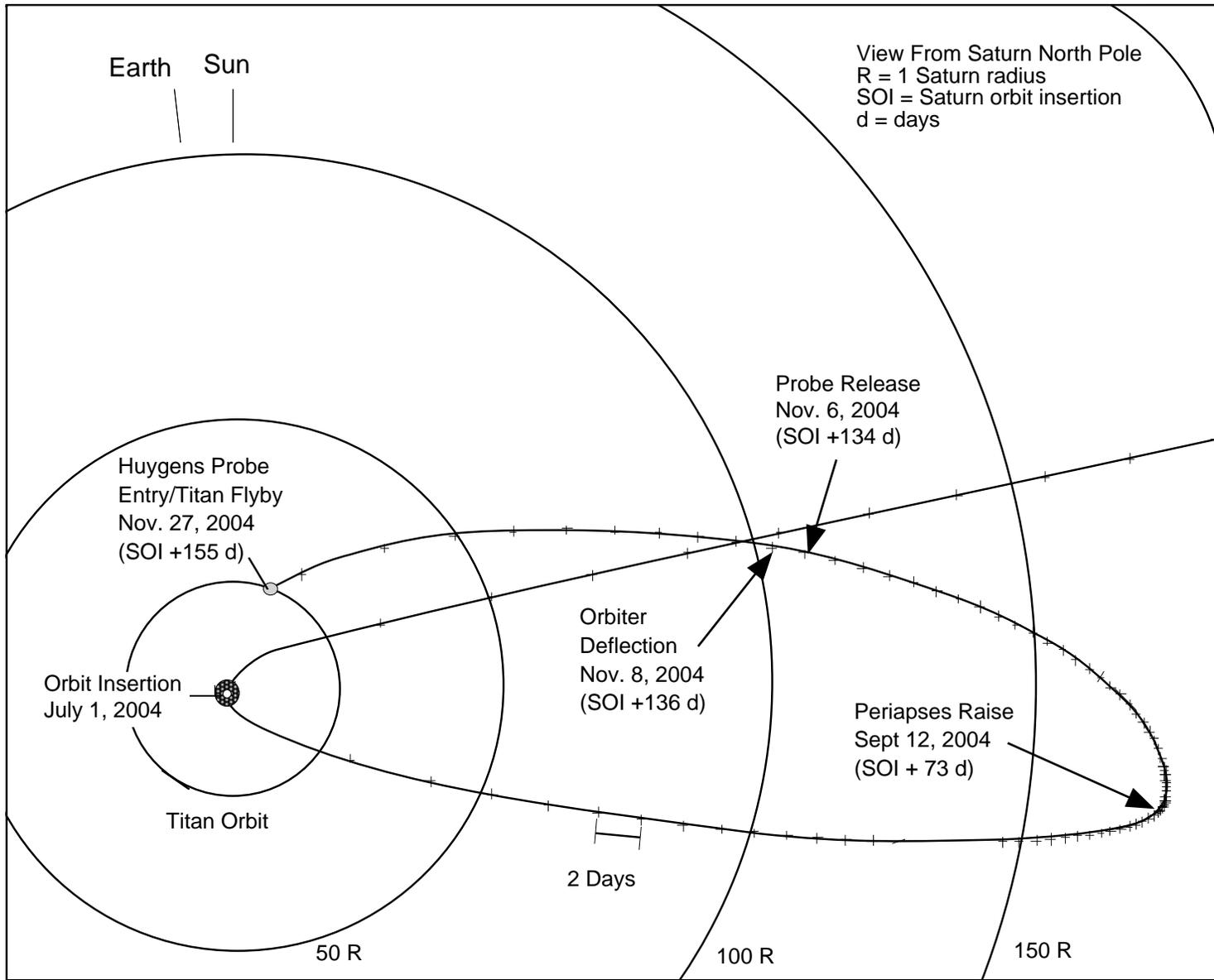
Approximately two days after launch, ground controllers will send to Cassini the sequence of computer commands to control the spacecraft for the following week. This sequence will include a trajectory correction maneuver in which Cassini fires its onboard thrusters to fine-tune its flight path. The next four or five command sequences sent to the spacecraft also will control the spacecraft for about one week each.

### **Cruise Phase**

In maneuvers called gravity-assist swingbys, Cassini will fly twice around Venus and once each past Earth and Jupiter. The spacecraft's speed relative to the Sun increases as it approaches and swings past each planet, giving Cassini the cumulative boost it needs to reach Saturn. The gravity-assist technique has been used extensively in the planetary exploration program to send spacecraft from one planet to another, and to increase a spacecraft's speed. In orbit around their respective planets, Galileo at Jupiter and Cassini at Saturn often use gravity assists to navigate from one large moon to the next.

Cassini will make two gravity-assist swingbys of Venus — one on April 25, 1998, at an altitude of about 300 kilometers (about 185 miles), and another on June 23, 1999, at an altitude of 1,530 kilometers (950 miles). These will be followed by a swingby of Earth occurring August 17, 1999, at an altitude of 800 kilometers (500 miles) or higher. As the spacecraft heads outward into the solar system it will make a swingby of Jupiter on December 30, 2000, passing within about 9,655,000 kilometers (about 6 million miles) of the planet.

Plans call for Cassini to carry out a low-activity flight plan during which only essential engineering and navigation activities such as trajectory correction maneuvers will be performed. The science instruments are planned to be turned off except for a few maintenance activities.



These include a single post-launch checkout of all of Cassini's science instruments, as well as calibration of Cassini's magnetometer during its subsequent Earth flyby. Huygens probe health checks are scheduled to occur every six months. No science observations are planned at Venus, Earth or Jupiter.

Two years before Saturn arrival, science instruments on the Cassini orbiter will be turned on, calibrated and begin collecting data.

## **Saturn Arrival**

The most critical phase of the mission after launch is Saturn orbit insertion. When Cassini reaches Saturn on July 1, 2004, the spacecraft will fire its main engine for 94 minutes to brake its speed and allow it to be captured as a satellite of Saturn. Passing through the dusty outermost ring of Saturn — called the E-ring — Cassini will swing close to the planet to begin the first of some six dozen orbits to be completed during the rest of its four-year primary mission.

The arrival period also provides a unique opportunity to observe Saturn's rings and the planet itself, as this is the closest approach the spacecraft will make to Saturn during the entire mission. A maneuver to lower the inclination of Cassini's orbit, called a periapsis-raise maneuver, will be performed in September 2004 to establish the geometry for the entry of the Huygens probe when it is released during Cassini's first Titan flyby.

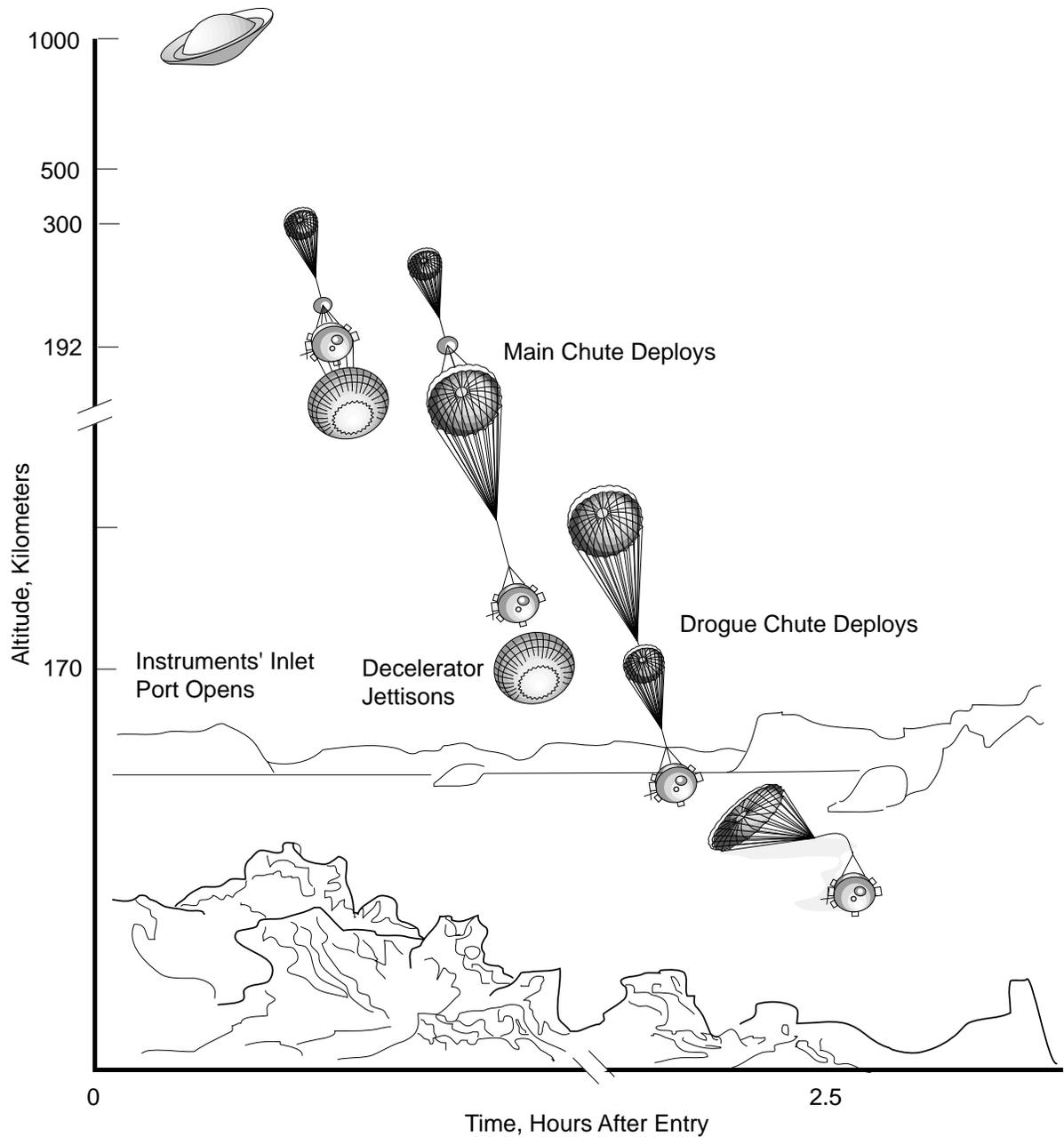
## **The Huygens Probe Mission**

The Huygens probe will be carried to Saturn's system by Cassini. Bolted to Cassini and fed electrical power through an umbilical cable, Huygens will ride along during the seven-year journey largely in a "sleep" mode, awakened every six months for three-hour instrument and engineering checkups.

Some 22 days before it hits the top of Titan's atmosphere, Huygens will be released from Cassini on November 6, 2004. With its umbilical cut and bolts released, Huygens will spring loose from the mother ship and fly on a ballistic trajectory to Titan. The probe will spin at 7 rpm for stability. Onboard timers will switch on the probe systems before the probe reaches Titan's upper atmosphere.

Two days after the probe's release, the orbiter will perform a deflection maneuver; this will keep Cassini from following Huygens into Titan's atmosphere. This maneuver will also establish the required geometry between the probe and the orbiter for radio communications during the probe descent; in addition, it will also set the initial conditions for Cassini's tour of Saturn's moons, which starts right after the completion of the Huygens probe mission.

The Huygens probe carries two microwave S-band transmitters and two antennas, both of which will transmit to the Cassini orbiter during the probe's descent. One stream of telemetry is delayed by about six seconds with respect to the other to avoid data loss if there are brief



*Huygens' descent to Titan*

transmission outages.

Probe descent will take place November 27, 2004. Huygens will enter Titan's atmosphere at a speed of some 20,000 kilometers per hour (about 12,400 miles per hour). It is designed to withstand the extreme cold of space (about -200 C (-330 F)) and the intense heat it will encounter during its atmospheric entry (12,000 C (more than 21,600 F)).

Huygens' parachutes will further slow the descent so the probe can conduct an intensive program of scientific observations all the way down to Titan's surface. When the probe's speed

has moderated to 1,400 kilometers per hour (about 870 miles per hour), the probe's after cover is pulled off by a pilot parachute. An 8.3-meter-diameter (27-foot) main parachute is then deployed to ensure a slow and stable descent. The main parachute slows the probe and allows the decelerator and heat shield to fall away when the parachute is released.

To limit the duration of the descent to a maximum of 2-1/2 hours, the main parachute is jettisoned 900 seconds after the probe has entered the top of the atmosphere. A smaller, 3-meter-diameter (9.8-foot) drogue chute deploys to support the probe for the remainder of the descent. The batteries and other resources are sized for a maximum mission duration of 153 minutes — including at least three minutes on the surface, but possibly up to a half an hour there if the descent takes less time than expected.

During the first part of the probe's descent, instruments onboard Huygens probe are controlled by a timer. During the final 10 to 20 kilometers (6 to 12 miles) of descent, instruments will be controlled on the basis of altitude measured by the radar altimeter.

Throughout the descent, Huygens' atmospheric structure instrument will measure more than six physical properties of the atmosphere. The gas chromatograph and mass spectrometer will determine the chemical composition of the atmosphere as a function of altitude. The aerosol collector and pyrolyzer will capture aerosol particles — fine liquid or solid particles suspended in the atmosphere — heat them and send the resulting vapor to the chromatograph/spectrometer for analysis.

Huygens' descent imager and spectral radiometer will take pictures of cloud formations and Titan's surface, and also determine the visibility within Titan's atmosphere. As the surface looms closer, the instrument will switch on a bright lamp and measure the spectral reflectance of the surface. Throughout the descent, the Doppler shift of Huygens' radio signal will be measured by the Doppler wind experiment onboard the Cassini orbiter to determine Titan's atmospheric winds, gusts and turbulence. As the probe is shifted about by winds, the frequency of its radio signal would change slightly in what is known as the Doppler effect — similar to how the pitch of a train whistle appears to rise and then fall as the train passes. Such changes in frequency can be used to deduce the wind speed experienced by the probe.

As Huygens nears impact, its surface science package will activate a number of instruments to measure surface properties. Huygens will impact the surface at about 25 kilometers per hour (15 miles per hour); the chief uncertainty is whether its landing will be a thud or a splash. If Huygens lands in liquid, these instruments will measure the liquid's properties while the probe floats for a few minutes.

If Huygens lands in liquid ethane it will not be able to return data for very long, because the extremely low temperature of this liquid (about -180 C (-290 F)) would prevent the batteries from operating. In addition, if liquid ethane permeates the probe's science instrument packages, the radio would be badly tuned and probably not operate.

Assuming Huygens continues to send data to Cassini from Titan's surface, it will be able

to do so for a maximum of about 30 minutes, when the probe's battery power is expected to run out and the Cassini orbiter disappears over the probe's horizon.

## **The Orbital Tour**

After the end of the Huygens mission, Cassini will continue its four-year orbital tour, consisting of more than 70 orbits around Saturn that will be shaped by gravity-assist flybys of Titan, or by firings of Cassini's thrusters or main engine. The size of these orbits, their orientation to the Saturn-Sun plane and their inclination to Saturn's equator are dictated by various scientific requirements. These include: imaging radar coverage of Titan's surface; flybys of selected icy moons, Saturn or Titan; occultations by Saturn's rings; and crossings of the ring plane.

Cassini will make at least six close targeted flybys of selected icy moons of greatest interest — Iapetus, Enceladus, Dione and Rhea. Images taken with Cassini's high-resolution telescopic cameras during these flybys will show surface features equivalent in size to a baseball diamond. At least two dozen more distant flybys (at altitudes of about 100,000 kilometers (about 60,000 miles)) will be made of the major moons of Saturn other than Titan. The varying inclination angle of Cassini's orbits also will allow studies of Saturn's polar regions in addition to the planet's equatorial zone.

Titan is the only Saturn moon large enough to enable significant gravity-assist changes in Cassini's orbits, though some of the other moons can help to accomplish more modest adjustments with their small gravitational effect on Cassini's flight path. Precise navigation and targeting of the point at which Cassini flies by Titan will be used to shape the orbital tour in the same way the Galileo mission has used its encounters of Jupiter's large moons to shape its Jovian tour.

## **End of Prime Mission**

The prime mission tour concludes on July 1, 2008, four years after Saturn arrival and 33 days after the last Titan flyby, which occurs on May 28, 2008. The aim point of the final flyby is chosen to position Cassini for a Titan flyby on July 31, 2008 — providing the opportunity to proceed with more flybys during an extended mission, if resources allow. Nothing in the design of the tour precludes an extended mission.

## **Mission Operations**

Two-way communication with Cassini will be through the large dish antennas of NASA's worldwide Deep Space Network. The spacecraft will transmit and receive in the microwave X-band, using either its parabolic high-gain antenna or one of its two low-gain antennas. The high-gain antenna is also used for radio and radar experiments and for receiving signals from the Huygens probe.

Because Cassini's science instruments are fixed and the entire spacecraft must be turned to point them, the spacecraft will be frequently reoriented by using either gyroscope-like reac-

tion wheels or the spacecraft's set of small onboard thrusters. Consequently, most science observations will be made without a real-time communications link to Earth. Data will be stored on Cassini's two solid-state data recorders, each with a capacity of about 2 gigabits (equivalent to about 200 megabytes each).

Each of Cassini's science instruments is run by a microprocessor capable of controlling the instrument and formatting/packetizing data. Ground controllers will run the spacecraft with a combination of some centralized commands to control system-level resources, and some commands issued by the individual science instruments' microprocessors. Packets of data will be collected from each instrument on a schedule that may vary at different times. Data packets are either stored on Cassini's onboard solid-state recorders or transmitted to Earth.

Mission controllers, engineering teams and science teams will monitor telemetry from the spacecraft and look for anomalies in real time. The flight systems operations team retrieves engineering data to determine the health, safety and performance of the spacecraft, and processes the tracking data to determine and predict the spacecraft's trajectory. Data will normally be received by the Deep Space Network with one tracking pass by one antenna per day, with occasional extra coverage for special radio science experiments.

Spacecraft operations during Cassini's interplanetary cruise will be centralized at JPL. During the Saturn tour, a system of distributed science operations will be implemented with centralized spacecraft control continuing at JPL. The concept is to allow scientists to operate their instrument from their home institution with as much ease as possible and with the minimum interaction necessary to collect their data.

### **Cost-Saving Approaches**

Because of the need to reduce the cost of activities before launch and during Cassini's nearly seven-year-long cruise, the development of many operations capabilities has been deferred until after launch.

The following are among choices made to reduce costs and simplify mission operations:

❑ *Limited science.* To reduce costs, there is no plan to acquire science data during Cassini's interplanetary cruise, including its flybys of Venus, Earth and Jupiter. The only exception is a gravitational wave experiment; this will attempt to detect gravitational waves emitted by supermassive objects such as quasars, active galactic nuclei or binary black holes.

❑ *Strict modes of operation.* Cassini's power system cannot supply enough electricity to run all science instruments simultaneously. In addition, science instruments cannot all be pointed optimally at the same time because of the fact that they are fixed to the body of the spacecraft. Mission planners therefore developed a concept of operational modes designed to reduce operational complexity. Under this approach, instruments will be operated in a series of standard, well-characterized configurations, identifying the on/off state of each instrument, minimum and maximum power and peak data rates allocated for each instrument, and states of the

engineering subsystems (radio, recorder, attitude and articulation control, and propulsion).

□ *Standardized, reusable sequence templates.* Ninety-eight percent of Cassini's Saturn tour will be conducted with a small number of reusable software modules and templates that dictate how science instruments are controlled. The remaining two percent (seven days per year) may consist of unique software command sequences developed for special occasions.

□ *No sequence team.* Mission planning and the development of command sequences will be led by "virtual teams" made up of representatives of the various science experiment or subsystem teams involved in a given procedure. This approach replaces the traditional custom of a "sequence team" responsible for developing the sequences of commands used to control the spacecraft and its instruments.

The Cassini program has remained on schedule and within budget since its inception.

# The Spacecraft

The Cassini spacecraft is a two-part structure, composed of the orbiter and the Huygens Titan probe. The orbiter is designed to enter orbit around Saturn; deliver Huygens to its destination and relay the probe's data; and conduct at least four years of detailed studies of Saturn's system. Huygens is designed to remain primarily dormant throughout Cassini's journey, then spring into action when it reaches the top of Titan's atmosphere. There, Huygens will deploy its parachutes and conduct 2-1/2 hours of intensive measurements as it descends through Titan's atmosphere, all the while transmitting its findings to the Cassini orbiter for relay back to Earth.

## The Cassini Orbiter

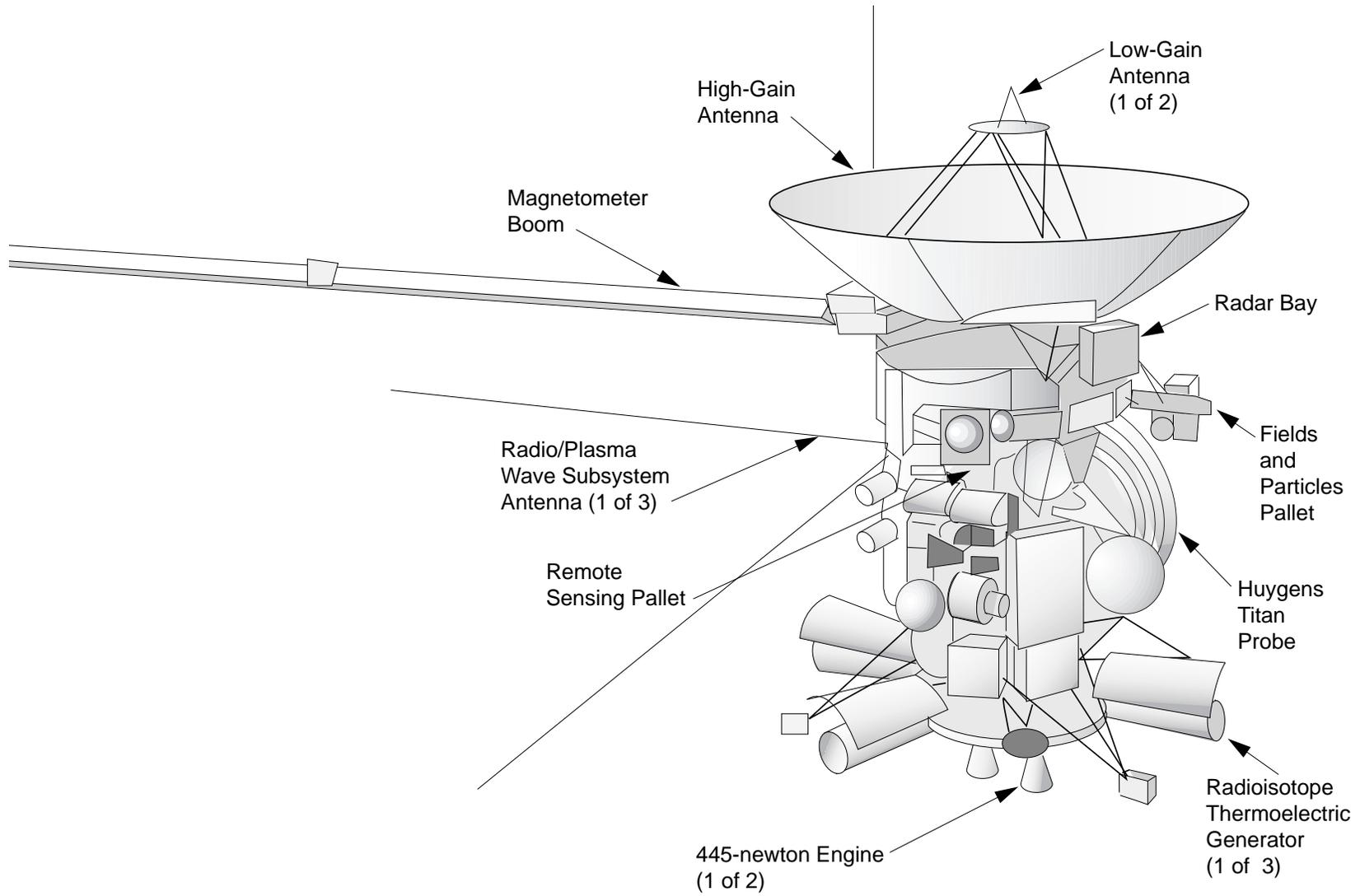
The Cassini orbiter alone weighs 2,125 kilograms (4,685 pounds). When the 320-kilogram (705-pound) Huygens probe and a launch vehicle adapter are attached, and 3,132 kilograms (6,905 pounds) of propellants are loaded, the spacecraft at launch will weigh 5,712 kilograms (12,593 pounds). More than half the spacecraft's mass is propellant — much of which is needed for Cassini's 94-minute main engine firing that brakes it into orbit around Saturn.

The spacecraft stands 6.8 meters (22.3 feet) high and is 4 meters (13 feet) wide. The magnetometer instrument is mounted on a 13-meter-long (42-foot) boom that extends outward from the spacecraft; three other rod-like antenna booms, each measuring 10 meters (about 32 feet), extend outward from the spacecraft in a Y-shape. Most of the spacecraft and its instrument housings are covered with multiple-layered, shiny amber-colored or matte-black blanket material. The blankets protect Cassini against the extreme heat and cold of space, and maintain the room temperature operating environment needed for computers and other electronic systems onboard. The blanketing includes layers of material like that used in bullet-proof vests to afford protection against dust-size particles called micrometeoroids that zip through interplanetary space.

The spacecraft's complexity is necessitated both by its flight path to Saturn and by the ambitious program of scientific observations to be accomplished at Saturn. Cassini has some 22,000 wire connections and more than 12 kilometers (7.5 miles) of cabling linking its instruments, computers and mechanical devices.

Cassini's cargo of science instruments, the Huygens probe and the enormous quantity of fuel the spacecraft needs to brake into orbit around Saturn make it the largest interplanetary spacecraft ever launched by the United States. (The former Soviet Union's Phobos 1 and 2 Mars craft each weighed 6,220 kilograms (13,713 pounds).) Cassini and Huygens, attached and fueled but without the launch vehicle adapter, weigh about 5,577 kilograms (12,295 pounds). More than half of that mass is liquid fuel. Cassini's fuel mass alone is more than the mass of the Galileo and Voyager spacecraft combined.

The main body of the orbiter is a nearly cylindrical stack consisting of a lower equipment module, a propulsion module and an upper equipment module, and is topped by the fixed



*Cassini spacecraft*

4-meter-diameter (13-foot) high-gain antenna. Attached about halfway up the stack are a remote sensing pallet, which contains cameras and other remote sensing instruments, and a fields and particles pallet, which contains instruments that study magnetic fields and charged particles. The two pallets carry most of the Cassini orbiter's science instruments. In general the whole spacecraft must be turned to point the instruments in the proper direction, though three of the instruments provide their own articulation about one axis.

Several booms will be deployed early in Cassini's flight. These include three rod-like plasma wave antennas and an 11-meter (40-foot) spring-loaded magnetometer boom that extends from a canister mounted on the upper equipment module.

Software sequences — detailed instructions stored in the spacecraft's computer — direct the activities of the spacecraft. A typical sequence may operate Cassini for a month without the need for intervention from ground controllers. Onboard computers are designed to withstand the radiation environment of deep space, particularly when the Sun is at peak activity. Solar flares, which can last up to several days, can deliver radiation 1,000 times above the usual radiation levels in interplanetary space. Cassini's electronics have undergone customized radiation hardening to ensure that they won't be disrupted or destroyed by such events.

Sophisticated fault protection software resides in the spacecraft's computers to continuously sample and sense the health of the onboard systems. The fault protection system automatically takes corrective action when it determines the spacecraft is at risk due to any onboard failure.

The orbiter receives electrical power from three radioisotope thermoelectric generators (RTGs). These generators produce power by converting heat into electrical energy. RTGs are not reactors, and the radioactive material is neither fissionable nor fusionable. Heat is provided by the natural radioactive decay of plutonium in a ceramic form of mostly plutonium-238; devices called thermocouples turn the heat into electricity to run the spacecraft. Upon arrival at Saturn, the three generators will provide about 675 watts of power. Plutonium dioxide is also used as the heat source in 82 small radioisotope heater units (RHUs) on the Cassini orbiter and 35 on the Huygens probe; each produces about 1 watt of heat to keep nearby electronics at their operating temperatures. RHUs were most recently used on Mars Pathfinder's Sojourner rover to keep its electronics warm during Martian nights. Both RTGs and RHUs have a long and safe heritage of use and high reliability in NASA's planetary exploration program, including the Voyager and Galileo missions.

Propulsion for major changes to Cassini's trajectory is provided by one of two main engines. These powerful engines use monomethylhydrazine as the fuel and nitrogen tetroxide as the oxidizer. Sixteen smaller engines called thrusters use hydrazine to control Cassini's orientation and to make small adjustments to the spacecraft's flight path.

Guidance and control is governed by sensors that recognize reference stars and the Sun, and by onboard computers that determine the spacecraft's position. Using a new type of gyroscope that vibrates rather than spins, the spacecraft can perform turns, twists and propulsion fir-

ings while retaining continuous knowledge of its own position. Unlike spacecraft such as Galileo, the Cassini orbiter is stabilized along all three axes and thus does not normally rotate during its long cruise to Saturn.

The mission's trajectory poses a challenge for controlling the spacecraft's temperature because in the first several years of the mission, the orbiter will be relatively close to the Sun. During this time, the high-gain antenna will be pointed at the Sun and used as a sunshade to shield the rest of the orbiter and probe. Special paints have been used on the antenna to reflect and radiate much of the sunlight received.

Communications with the spacecraft during its passage through the inner solar system will be through one of the orbiter's two low-gain antennas. In late January 2000, as Cassini enters the cooler climes of the asteroid belt and beyond, it will turn its high-gain antenna toward Earth and conduct telecommunications through it for the remainder of the mission.

As Cassini moves farther from the Sun, extreme cold becomes a concern. At Saturn's distance, the intensity of sunlight is approximately 1 percent that at Earth.

Heat within the spacecraft is retained by using lightweight, multiple-layered insulating blankets that have been tailor-made for the instrument housings and other areas of the orbiter. The blanket's outer layer is a three-ply membrane composed of a Kapton core with an aluminized inner surface and a metallic outer surface. The translucent Kapton has a yellow color, and when backed by a shiny aluminum layer, results in an amber appearance. Up to 26 layers of material are used in the blankets, which also afford protection against dust-size micrometeoroids which, traveling at speed of 5 to 40 kilometers per second (about 10,000 to 90,000 miles per hour) could otherwise potentially penetrate portions of the spacecraft.

## **Orbiter Subsystems**

The Cassini orbiter contains 12 engineering subsystems that govern spacecraft features and functions including wiring, electrical power, computing, telecommunications, guidance and propulsion.

□ The **structure subsystem** is the skeleton that provides mechanical support and alignment for all flight equipment, including the Huygens probe. In addition, it provides an equipotential container — an electrical grounding reference — which provides a shield from radio frequency interference, and protection from space radiation and micrometeoroids. The structure subsystem consists of the upper equipment module, which contains the 12-bay electronics bus assembly, instrument pallets and the magnetometer boom; the lower equipment module; plus all the brackets and structure used to attach the Huygens probe, the low-gain and high-gain antennas, electrical generators, main rocket engines, reaction control thrusters and other equipment. The structure subsystem also includes the adapter which supports the spacecraft on the Centaur upper stage during launch.

□ The **radio frequency subsystem** provides the telecommunications facilities for the spacecraft, and is also used as part of the radio science instrument. For communications, it produces an X-band carrier signal at a frequency of 8.4 GHz; modulates it with data received from the command and data subsystem; amplifies the X-band carrier power to produce 20 watts from the traveling wave tube amplifiers; and delivers the signal to the antenna subsystem. (The 20 watts is expected to degrade to about 19 watts by the time Cassini reaches Saturn.) From the antenna subsystem, the radio frequency subsystem takes signals transmitted from Earth at a frequency of 7.2 GHz in the microwave X-band; demodulates them; and delivers the commands and data to the command data subsystem for storage and/or execution.

□ Regulated electrical power and various small pyrotechnic devices on the spacecraft are controlled by the **power and pyrotechnics subsystem**. Operating on command from the central computer system, this subsystem distributes electrical power to instruments and other subsystems on the spacecraft at 30 volts DC. The subsystem also regulates a shunt radiator that can be used to dispose of excess heat. Pyrotechnics include squib devices that will be fired to cut cables and other links that hold the Huygens probe onto the orbiter.

□ The **command and data subsystem** is Cassini's nervous system — the central processing and delivery clearinghouse of the spacecraft for commands received from the ground and data sent back to Earth. All elements of the subsystem are duplicated with redundant components that can be used in the event of a component failure. The subsystem receives ground commands and data from the radio frequency subsystem, processes the information and distributes it to other subsystems. The command and data subsystem uses one each of the two redundant solid-state recorders and flight computers, which are programmed in the Ada programming language. Memory capacity for each solid-state recorder is 2 gigabits.

Scientific and engineering data from science instruments destined for transmission to Earth are first forwarded to the command and data subsystem for processing and formatting for telemetry, and delivery to the radio frequency subsystem. The command and data subsystem contains software routines that protect the spacecraft in the event of a fault. The software also allows the spacecraft to autonomously respond to faults needing immediate action. Memory for the command and data subsystem is 512 kilo-words of random-access memory (RAM) and 8 kilo-words of programmable read-only memory (PROM).

□ The **attitude and articulation control subsystem** is the spacecraft's inner ear, continuously sensing and measuring the spacecraft's orientation on its three axes and the spacecraft's position in space relative to Earth, Sun, Saturn and other targets. It provides measurements and controls pointing for spacecraft instruments, including scans that require the spacecraft to roll while an instrument performs an observation. The attitude and articulation control subsystem encompasses a number of sensors including redundant Sun sensor assemblies; stellar reference units, or star trackers; a Z-axis accelerometer; and two 3-axis gyro inertial reference units. Each unit consists of four gyros, three orthogonal to each other and the fourth skewed equidistant to the other three. The subsystem also contains actuators for the main rocket engine gimbals and for the redundant reaction wheel.

With two redundant computers programmed in Ada, the subsystem processes commands from the command and data subsystem and produces commands to be delivered to attitude control actuators and/or spacecraft thrusters or main engines to control Cassini's attitude and to make trajectory changes. The attitude and articulation control subsystem memory has 512 kilobytes of RAM and 8 kilobytes of PROM.

□ All power and data cabling, except for coaxial cabling and waveguides, make up the **cabling subsystem**. This network of cabling conducts power from the three electrical generators to the power and pyrotechnics subsystem and to the power shunt radiator. It also conducts data between the command and data subsystem and the other subsystems and assemblies on the spacecraft. In addition, cabling allows engineers to access Cassini's electronics during spacecraft integration and testing.

□ The **propulsion module subsystem** controls the spacecraft's thrust and changes in its attitude. It works under the command of the attitude and articulation control system. Attitude control is provided by the reaction control subsystem, which consists of four clusters of four hydrazine thrusters each. These move the spacecraft to or maintain it in its desired orientation and are used to point the instruments at their targets. The thrusters are also used for executing small spacecraft maneuvers. For larger changes in the spacecraft velocity, the main rocket engine is used. Cassini has a primary and redundant pressure-regulated main engine. Each engine is capable of a thrust of approximately 445 newtons (100 pounds of force). The bipropellant main engines burn nitrogen tetroxide and monomethylhydrazine. The engines are gimballed so that the thrust vector can be maintained through the shifting center of mass of the spacecraft. Mounted below the main engines is a retractable cover that is used during cruise to protect the main engines from micrometeoroids. The main engine cover can be extended and retracted multiple times (at least 25 times), and has a pyro-ejection mechanism to jettison the cover should there be a mechanical problem with the cover that interferes with main engine operation. During cruise the cover will remain closed when the main engines are not in use.

□ The **temperature control subsystem** keeps temperatures of the various parts of the spacecraft within allowable limits through a variety of thermal control techniques, many of which are passive. Automatically positioned reflective louvers are located on Cassini's 12-bay electronics bus. Radioisotope heater units are used where constant heat is required. Multilayer insulation blankets cover much of the spacecraft and its equipment. Electric heaters are used in several locations under control of the spacecraft's main computer. Temperature sensors are located at many sites on the spacecraft, and their measurements are used by the command data subsystem to adjust the heaters. The entire spacecraft body and Huygens probe are shaded when necessary by the high-gain antenna.

□ The **mechanical devices subsystem** provides a pyrotechnic separation device that releases the spacecraft from the launch vehicle adapter. Springs then push the spacecraft away from the adapter. The subsystem includes a self-deploying 10.5-meter (40-foot) coiled mast stored in a canister which supports the magnetometers. It also includes an articulation system for a backup reaction wheel assembly, a "pin puller" for the rod-like antennas of the radio plasma wave spectrometer's Langmuir probe, and louvers for venting or holding heat from the

radioisotope heater units.

❑ The **electronic packaging subsystem** consists of the electronics packaging for most of the spacecraft in the form of the 12-bay electronics bus.

❑ The **solid-state recorder** is the primary memory storage and retrieval device for the orbiter. The spacecraft is equipped with two recorders, each with a capacity of 2 gigabits (1.8 gigabits at end of mission). Before completion of the Huygens descent probe's mission, only one recorder can be used at any time to store science data from the mission. After the Huygens mission, however, both recorders may be used to record and play back science data. Data such as spacecraft telemetry and memory loads for various subsystems may be stored in separate files, or partitions, on the recorder. All data recorded to and played back from the solid-state recorder are handled by the command data subsystem.

❑ The **antenna subsystem** provides a directional high-gain antenna that can transmit and receive on four different bands in the microwave spectrum — X, Ka, S and Ku. The high-gain antenna and low-gain antenna #1 are provided by the Italian space agency. Low-gain antenna #1 is located on the dish structure of the high-gain antenna. Low-gain antenna #2 is located on the Cassini orbiter body below the attach point for the Huygens probe. During the inner solar system cruise, the high-gain antenna is pointed toward the Sun to provide shade for the spacecraft. The two low-gain antennas allow for one or the other to transmit and receive signals in the microwave X-band to and from Earth when the spacecraft is Sun-pointed. The low-gain antennas also provide an emergency telecommunications capability while Cassini is at Saturn.

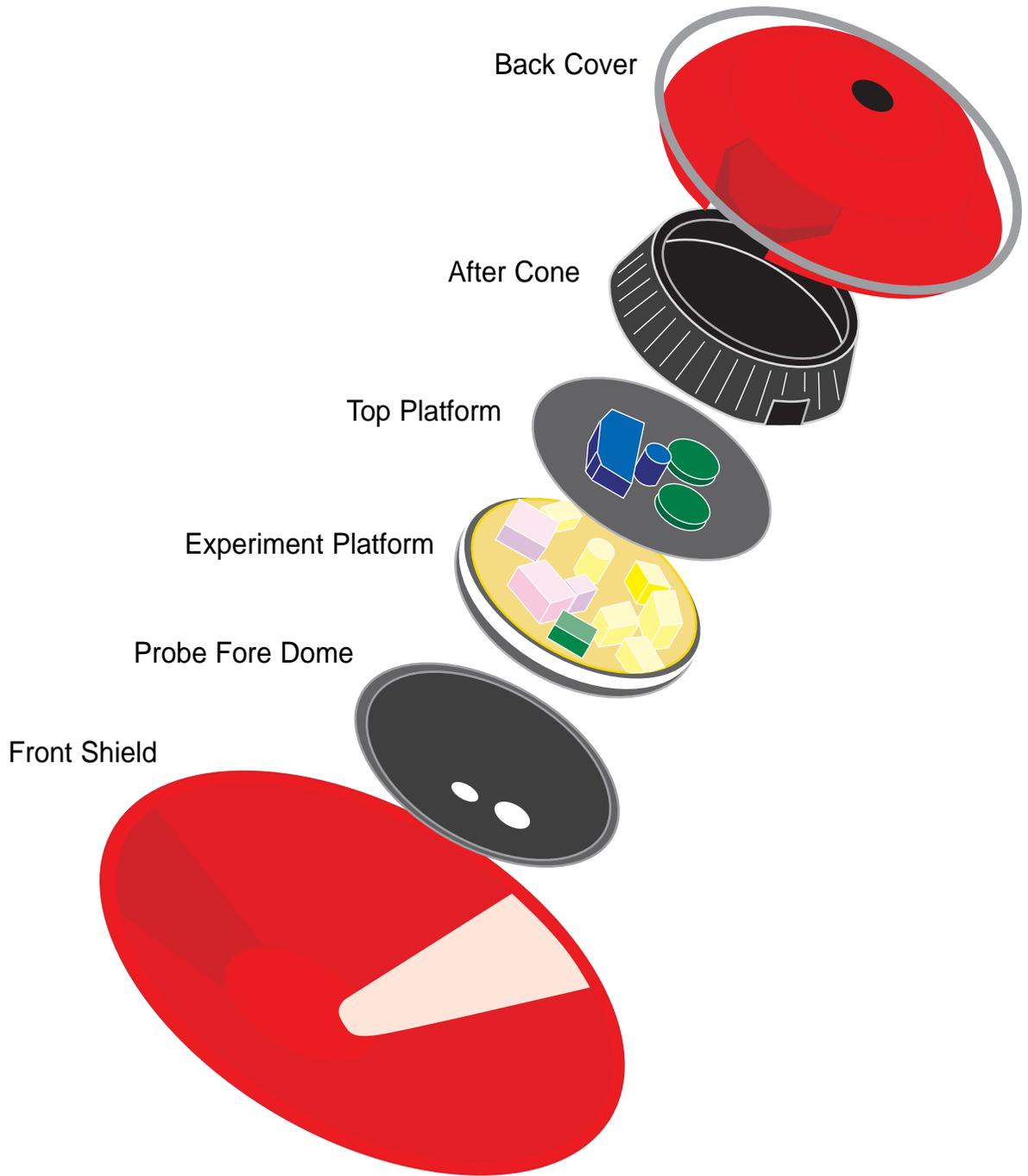
## The Huygens Probe

The Huygens probe system includes the probe itself, which enters the Titan atmosphere, and support equipment that remains attached to the orbiter. The probe weighs 320 kilograms (705 pounds) and consists of three main elements:

❑ A *spin-eject device*, which uses springs to propels the probe away from the orbiter with a relative velocity of 0.3 to 0.4 meter per second (about 1 foot per second) and simultaneously causes the probe to spin about its axis of 7 rpm. This device is part of the support equipment.

❑ A *front shield*, 2.7 meters (8.8 feet) in diameter, covered with a special thermal protection material called AQ60, a low-density mat of silica fibers, to protect the probe from the enormous heat generated during entry into Titan's atmosphere.

❑ An *aft cover* that uses thermal protection materials to ensure a slow and stable descent. The main parachute slows the probe and allows the decelerator to fall away when it is released. To limit the duration of the descent to a maximum of 2.5 hours, the main parachute is jettisoned at 900 seconds after atmospheric entry, and is replaced by a 3-meter-diameter (about 10-foot) drogue chute for the remainder of the descent.



*Huygens probe*

**Inner structure.** The probe's interior consists of two aluminum honeycomb platforms and an aluminum shell. It is linked by fiberglass struts and pyrotechnically operated release mechanisms to the front shield and aft cover. The central equipment platform carries, on both its upper and lower surfaces, the boxes containing the electrical subsystems and the experiments. The upper platform carries the stowed parachute and the transmitter used to radio data in the microwave S-band to the Cassini orbiter.

**Thermal control.** At different phases of the mission, Huygens will be subjected to extremes of heat and cold requiring a variety of passive controls to maintain the required temperature conditions. When the spacecraft is nearer the Sun on the Venus and Earth legs of its trajectory, the probe will receive high solar heat input, but will get some protection by being shaded by the orbiter's high-gain antenna. Multilayered thermal blanketing, which burns off later during Titan atmospheric entry, will also protect the probe from solar heating.

When Cassini leaves the inner solar system, the temperature of the probe will be greatly reduced. After separation from the Cassini orbiter, Huygens will be at its coldest. To ensure that the equipment stays operational, 25 radioisotope heater units (RHUs) are placed in the system. Each RHU, which contains radioactive plutonium dioxide, produces about 1 watt of heat.

During entry into Titan's atmosphere, the front shield may reach temperatures above 1,500 C (2,700 F). Layers of insulation will ensure that the equipment inside stays below 50 C (122 F). Once the chutes are deployed, the probe instruments will be exposed to the cold Titan atmosphere at a temperature of -200 C (-330 F). The internal temperature will be kept within operating limits by thick foam insulation filling the probe and by power dissipation in the experiments and subsystems.

**Electrical power.** While it is still attached to the Cassini orbiter, the Huygens probe will obtain power from the orbiter via an umbilical cable. After separation, electrical power is provided by five lithium sulfur dioxide batteries, each with 23 cells. Much of the battery power is used to power the Huygens probe's timer for the 22 days of coasting to Titan.

**Command and data management.** Huygens' command and data management subsystem controls the timing and execution of a number of critical events. It times the coast phase, and switches on the probe just before entry. It controls deployment of various components during descent. It distributes commands to other subsystems and to the experiments. It distributes to the experiments information that provides a timeline of conditions that instruments can use to schedule operations. And it collects scientific and engineering data and forwards them to the orbit during the cruise to Saturn and during the Titan mission.

**Probe data relay.** The probe data relay subsystem provides the one-way communications link between the Huygens probe and the Cassini orbiter, and includes equipment installed in each spacecraft. Elements that are part of the probe support equipment on the Cassini orbiter include radio frequency electronics (including an ultra-stable oscillator) and a low-noise amplifier. For backup, the Huygens probe carries two S-band transmitters, both of which transmit

during probe descent, each with its own antenna. The telemetry in one link is delayed by about six seconds with respect to the other to avoid data loss if there are brief transmission outages. Reacquisition of the probe signal would normally occur within this interval.

## **New Technology**

A wealth of new technology was developed and qualified for spaceflight by or for the Cassini program. Much of this new technology has already been adopted by other space science programs, in some cases at a discounted cost directly attributable to Cassini. This has enabled the development of new classes of low-cost, high-efficiency spacecraft, such as the Discovery and New Millennium spacecraft.

The Cassini orbiter advances and extends the technology base of the United States and its partners with several innovations in engineering and information systems. Whereas previous planetary spacecraft used onboard tape recorders to store data, Cassini has pioneered a new solid-state data recorder with no moving parts. The new recorder eventually will replace tape recorders on all space missions. NASA's Advanced X-ray Astrophysics Facility (AXAF), for example, will use a solid-state recorder from the production line established for the Cassini mission. In addition, the recorder has great potential for use in a variety of fields, from aerospace to the entertainment industry, and is expected to find wide applicability in consumer electronics.

Similarly, the main onboard computer that directs operations of the orbiter uses a novel design that draws on new families of electronic chips. Among them are very high-speed integrated circuit (VHSIC) chips developed under a U.S. government-industry research and development initiative. The Cassini application GVSC 1750A computer is the first civilian spacecraft application of this technology. The computer system also uses power new application-specific integrated circuit (ASIC) parts; each component replaces one hundred or more traditional chips. The ASIC chips allow the development of a data system for Cassini 10 times more efficient than earlier spacecraft designs, but at less than one-third the mass and volume. Two missions under NASA's Discovery program, Mars Pathfinder and the Near Earth Asteroid Rendezvous (NEAR), used these chips directly off the Cassini production line.

Elsewhere on the Cassini orbiter, the power system benefits from an innovative solid-state power switch developed for the mission. This switch eliminates rapid fluctuations called transients that usually occur with conventional power switches, with a significantly improved component lifetime. The power switch holds great promise for use in numerous Earth-based applications. A low mass, low power, radiation-hardened X-band radio transponder (a combined receiver and transmitter) was developed by the Cassini program. Both Mars Pathfinder and NEAR missions used radio transponders built on the Cassini mission's production line.

The inertial reference units to be used on Cassini represent the first space version of a revolutionary new gyro called the hemispherical resonator gyroscope. Gyros commonly used in spacecraft, aircraft and ships are large, very delicate mechanical devices whose many moving parts make them susceptible to failure. This new gyro, which eventually may be used on other spacecraft, promises greater reliability and less vulnerability to failure because it uses no mov-

ing parts. A slightly modified Cassini gyro was incorporated into the NEAR spacecraft.

### **Cassini Signature Disk**

In August 1997, a small digital versatile disk (DVD) was installed aboard the Cassini spacecraft during processing at the Kennedy Space Center. The disk contains a record of 616,400 handwritten signatures from 81 countries around the globe. Signatures were received from people of all ages and backgrounds.

Mail came from individuals, families and, often, from entire schools of students. Signatures came from the very young, just learning to write, and from the very old, whose hands were no longer steady. Signatures were sent in behalf of loved ones who had died in the recent past. Even the signatures of Jean-Dominique Cassini and Christiaan Huygens were obtained from letters they wrote during the 17th century.

Sorting, counting and scanning the signatures was performed over the course of a year by volunteers from the Planetary Society, Pasadena, CA. The disk's cover, designed by Charles Kohlhase of the Cassini project, depicts a golden eagle wing feather and various Cassini mission elements to symbolize the signature experience. The feather was chosen to represent both the beauty and power of flight, as well as the quill pen that was used for nearly 14 centuries in writing and signing.

# Science Objectives

Cassini's payload represents a carefully chosen set of interrelating instruments that will address many major scientific questions about the Saturn system. The data they return will be analyzed by a team of nearly 300 scientists from the United States and Europe. The Cassini and Huygens mission science objectives are as follows:

## Saturn

- Determine the temperature field, cloud properties and composition of Saturn's atmosphere.
- Measure the planet's global wind field, including waves and eddies; make long-term observations of cloud features to see how they grow, evolve and dissipate.
- Determine the internal structure and rotation of the deep atmosphere.
- Study daily variations and relationship between the ionosphere and the planet's magnetic field.
- Determine the composition, heat flux and radiation environment present during Saturn's formation and evolution.
- Investigate sources and nature of Saturn's lightning.

## Titan

- Determine the relative amounts of different components of the atmosphere; determine the mostly likely scenarios for the formation and evolution of Titan and its atmosphere.
- Observe vertical and horizontal distributions of trace gases; search for complex organic molecules; investigate energy sources for atmospheric chemistry; determine the effects of sunlight on chemicals in the stratosphere; study formation and composition of aerosols (particles suspended in the atmosphere).
- Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning.
- Determine the physical state, topography and composition of Titan's surface; characterize its internal structure.
- Investigate Titan's upper atmosphere, its ionization and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

## **Magnetosphere**

Determine the configuration of Saturn's magnetic field, which is nearly symmetrical with Saturn's rotational axis. Also study its relation to the modulation of Saturn kilometric radiation — a radio emission from Saturn that is believed to be linked to the way electrons in the solar wind interact with the magnetic field at Saturn's poles.

Determine the current systems, composition, sources and concentrations of electrons and protons in the magnetosphere.

Characterize the structure of the magnetosphere and its interactions with the solar wind, Saturn's moons and rings.

Study how Titan interacts with the solar wind and with the ionized gases within Saturn's magnetosphere.

## **The Rings**

Study configuration of the rings and dynamic processes responsible for ring structure.

Map the composition and size distribution of ring material.

Investigate the interrelation of Saturn's rings and moons, including imbedded moons.

Determine the distribution of dust and meteoroid distribution in the vicinity of the rings.

Study the interactions between the rings and Saturn's magnetosphere, ionosphere and atmosphere.

## **Icy Moons**

Determine general characteristics and geological histories of Saturn's moons.

Define the different physical processes that have created the surfaces, crusts or sub-surfaces of the moons.

Investigate compositions and distributions of surface materials, particularly dark, organic-rich materials and condensed ices with low melting points.

Determine the bulk compositions and internal structures of the moons.

Investigate interactions of the moons with Saturn's magnetosphere and ring system

and possible gas injections into the magnetosphere.

In addition to the science objectives at Saturn, the Cassini spacecraft will also conduct a gravity-wave investigation through the ASI-provided high-gain antenna during its interplanetary cruise.

### **Orbiter Science Instruments**

The Cassini orbiter carries a total of 12 science instruments. Two pallets carry most of the instruments; four instruments are located on the remote sensing experiments pallet, and three are located on the fields and particles experiments pallet. Others are fixed at independent locations on the spacecraft. The experiments include:

□ **Imaging Science Subsystem**, or Cassini's cameras, will photograph a wide variety of targets — Saturn, the rings, Titan and the icy moons — from a broad range of observing distances for various scientific purposes. General science objectives include studying the atmospheres of Saturn and Titan, the rings of Saturn and their interactions with the planet's moons and the surface characteristics of the moons, including Titan. The instrument includes both a narrow-angle and a wide-angle camera. The narrow-angle camera provides high-resolution images of targets of interest, while the wide-angle camera provides more extended spatial coverage at lower resolution. The cameras can also obtain optical navigation frames — images of Saturn's moons against a star background — which are used to keep the spacecraft on the correct trajectory. Team leader is Dr. Carolyn C. Porco of the University of Arizona, Tucson, AZ.

□ **Visible and Infrared Mapping Spectrometer** will map the surface spatial distribution of the mineral and chemical features of a number of targets, including Saturn's rings, surfaces of the moons, and the atmospheres of Saturn and Titan. The instrument includes a pair of imaging grating spectrometers that are designed to measure reflected and emitted radiation from atmospheres, rings and surfaces to determine their compositions, temperatures and structures. A spectrometer is an optical instrument that splits the light received from objects into its component wavelengths; each chemical has a unique spectral signature and thus can be identified. The instrument obtains information over 352 contiguous wavelengths from 0.35 to 5.1 micrometers; it measures intensities of individual wavelengths and uses the data to infer the composition and other properties of the object that emitted the light. The mapping spectrometer provides images in which every pixel contains high-resolution spectra of the corresponding spot on the target body. Principal investigator is Dr. Robert H. Brown of the University of Arizona, Tucson, AZ.

□ **Composite Infrared Spectrometer** will measure infrared emissions from atmospheres, rings and surfaces. This spectrometer will create vertical profiles of temperature and gas composition for the atmospheres of Titan and Saturn, from deep in their tropospheres (lower atmospheres), to high in their stratospheres (upper atmospheres). The instrument will also gather information on the thermal properties and composition of Saturn's rings and icy moons. The instrument is a coordinated set of three interferometers designed to measure infrared emissions over wavelengths from 7 to 1000 micrometers in the mid- and far-infrared range of the electromagnetic spectrum. Each interferometer uses a beam splitter to divide incoming infrared light

into two paths. The beam splitter reflects half of the energy toward a moving mirror and transmits half to a fixed mirror. The light is recombined at the detector. As the mirror moves, different wavelengths of light alternately cancel and reinforce each other at a rate that depends on their wavelengths. This information can be used to construct an infrared spectrum. Principal investigator is Virgil G. Kunde of NASA's Goddard Space Flight Center, Greenbelt, MD.

❑ **Ultraviolet Imaging Spectrograph** is a set of detectors designed to measure ultraviolet light reflected by or emitted from atmospheres, rings and surfaces to determine their compositions, distributions, aerosol content and temperatures. The instrument will also measure fluctuations of sunlight and starlight as the Sun and stars move behind the rings of Saturn and the atmospheres of Saturn and Titan, and will determine the atmospheric concentrations of hydrogen and deuterium. The instrument includes a two-channel, far- and extreme-ultraviolet imaging spectrograph that studies light over wavelengths from 55.8 to 190 nanometers. It also has a hydrogen deuterium absorption cell and a high-speed photometer. An imaging spectrograph records spectral intensity information in one or more wavelengths of light and then outputs digital data that can be displayed in a visual form, such as a false-color image. The hydrogen-deuterium absorption cell measures the quantity of deuterium, a heavier form of hydrogen. The high-speed photometer determines the radial structure of Saturn's rings by watching starlight through the rings. Principal investigator is Dr. Larry L. Esposito of the University of Colorado, Boulder, CO.

❑ **Cassini Radar** will investigate the surface of Saturn's largest moon, Titan. Titan's surface is covered by a thick, cloudy atmosphere that is hidden to normal optical view, but can be penetrated by radar. The instrument is based on the same imaging radar technology used in missions such as Magellan to Venus and the Earth-orbiting Spaceborne Imaging Radar. Scientists hope to determine if oceans exist on Titan and, if so, determine their distribution; investigate the geological features and topography of Titan's solid surface; and acquire data on other targets, such as Saturn's rings and icy moons, as conditions permit.

The radar will take four types of observations: *imaging*, *altimetry*, *backscatter* and *radiometry*. In *imaging* mode, the instrument will bounce pulses of microwave energy off the surface of Titan from different incidence angles and record the time it takes the pulses to return to the spacecraft. These measurements, converted to distances by dividing by the speed of light, will allow construction of visual images of the target surface with a resolution ranging from one third of a kilometer to 1.7 kilometers (about one-fifth mile to one mile).

Radar *altimetry* similarly involves bouncing microwave pulses off the surface of the target body and measuring the time it takes the "echo" to return to the spacecraft. In this case, however, the goal will not be to create visual images but rather to obtain numerical data on the precise altitude of surface features. The altimeter resolution is 24 to 27 kilometers horizontally, 90 to 150 meters vertically (about 14 to 16 miles horizontally, 297 to 495 feet vertically).

In *backscatter mode*, the radar bounces pulses off Titan's surface and measures the intensity of the energy returning. This returning energy, or backscatter, is always less than the original pulse, because surface features inevitably reflect the pulse in more than one direction.

From the backscatter measurements, scientists can draw conclusions about the composition and roughness of the surface.

In *radiometry* mode, the radar will operate as a passive instrument, simply recording the heat energy emanating from the surface of Titan. This information can be used to determine the amount of moisture (such as vapors of methane) in Titan's atmosphere, a factor that has an impact on the precision of the other measurements taken by the instrument.

At altitudes between 22,500 and 9,000 kilometers (about 14,000 to 5,600 miles), the radar will switch between scatterometry and radiometry to obtain low-resolution global maps of Titan's surface roughness, backscatter intensity and thermal emissions. At altitudes between 9,000 and 4,000 kilometers (about 5,600 to 2,500 miles), the instrument will switch between altimetry and radiometry, collecting surface altitude and thermal emission measurements. Below 4,000 kilometers (about 2,500 miles), the radar will switch between imaging and radiometry. Team leader is Dr. Charles Elachi of NASA's Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

□ **Radio Science** will use the spacecraft's radio and the ground antennas of NASA's Deep Space Network to study the composition, pressures and temperatures of the atmospheres and ionospheres of Saturn and Titan; the radial structure of and particle size distribution in Saturn's rings; and the masses of objects in the Saturn system and the mass of Saturn's ring system as a whole. Radio science will also be used to search for gravitational waves coming from beyond our solar system. Some of these experiments measure Doppler shifts (frequency shifts) and other changes to radio signals that occur when the spacecraft passes behind planets, moons, atmospheres or physical features such as planetary rings. From these measurements, scientists can derive information about the structures and compositions of the occulting bodies, atmospheres and the rings. Team leader is Dr. Arvydas J. Kliore of NASA's Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

□ **Cassini Plasma Spectrometer** will measure the composition, density, flow velocity and temperature of ions and electrons in Saturn's magnetosphere. The instrument consists of three sensors: an electron spectrometer, an ion beam spectrometer and an ion mass spectrometer. A motor-driven actuator rotates the sensor package to provide 208-degree scanning in the azimuth of the Cassini orbiter. The electron spectrometer makes measurements of the energy of incoming electrons; its energy range is 0.7 to 30,000 electronvolts. The ion beam spectrometer determines the energy to charge ratio of an ion; its energy range is 1 electronvolt to 50 kiloelectronvolts. The ion mass spectrometer's energy range is 1 electronvolt to 50 kiloelectronvolts. Principal investigator is Dr. David T. Young of the Southwest Research Institute, San Antonio, TX.

□ **Ion and Neutral Mass Spectrometer** will determine the composition and structure of positive ion and neutral particles in the upper atmosphere of Titan and the magnetosphere of Saturn, and will measure the positive ion and neutral environments of Saturn's icy moons and rings. The instrument will determine the chemical, elemental and isotopic composition of the gaseous and volatile components of the neutral particles and the low energy ions in Titan's

atmosphere and ionosphere, Saturn's magnetosphere and the ring environment. Team leader is Dr. J. Hunter Waite of the Southwest Research Institute, San Antonio, TX.

❑ **Cosmic Dust Analyzer** will provide direct observations of small ice or dust particles in the Saturn system in order to investigate their physical, chemical and dynamic properties and study their interactions with the rings, icy moons and magnetosphere of Saturn. The instrument measures the amount, velocity, charge, mass and composition of tiny dust and ice particles. It has two types of sensors — high-rate detectors and a dust analyzer. The two high-rate detectors, intended primarily for measurements in Saturn's rings, count impacts up to 10,000 per second. The dust analyzer determines the electric charge carried by dust particles, the flight direction and impact speed, mass and chemical composition, at rates up to 1 particle per second, and for speeds of 1-100 kilometers per second (up to about 60 miles per second). An articulation mechanism allows the entire instrument to be rotated or repositioned relative to the body of the Cassini orbiter. Principal investigator is Dr. Eberhard Grün of the Max Planck Institute für Kernphysik, Heidelberg, Germany.

❑ **Dual Technique Magnetometer** will determine the magnetic fields of the planet and moons and study dynamic interactions between different magnetic fields in the planetary environment. The instrument consists of direct-sensing instruments that detect and measure the strength of magnetic fields in the vicinity of the spacecraft. The experiment includes both a flux gate magnetometer and a vector/scalar helium magnetometer. They are used to measure the magnitude and direction of magnetic fields. Since magnetometers are sensitive to electric currents and ferrous components, they are generally placed on an extended boom, as far from the spacecraft as possible. On Cassini, the flux gate magnetometer is located midway out on the 11-meter (36-foot) magnetometer boom, and the vector/scalar helium magnetometer is located at the end of the boom. The boom itself, composed of thin, nonmetallic rods, is folded during launch and deployed about two years after launch. The magnetometer electronics are in a bay in the Cassini orbiter's spacecraft body. Principal investigator is Dr. David J. Southwood of the Imperial College of Science & Technology, London, England.

❑ **Magnetospheric Imaging Mass Spectrometer** is designed to measure the composition, charge state and energy distribution of energetic ions and electrons; detect fast neutral particles; and conduct remote imaging of Saturn's magnetosphere. It is the first instrument ever designed to produce an image of a planetary magnetosphere. This information will be used to study the overall configuration and dynamics of the magnetosphere and its interactions with the solar wind, Saturn's atmosphere, Titan, rings and the icy moons. The instrument will provide images of the ionized gases, called plasma, surrounding Saturn and determine the charge and composition of ions. Like the Cassini plasma spectrometer, this instrument has three sensors that perform various measurements: the low-energy magnetospheric measurement system, the charge-energy-mass spectrometer and the ion and neutral camera. The low-energy magnetospheric measurement system will measure low- and high-energy proton, ion and electron angular distributions (the number of particles coming from each direction). The charge-energy-mass spectrometer uses an electrostatic analyzer, a time-of-flight mass spectrometer and microchannel plate detectors to measure the charge and composition of ions. The third sensor, the ion and neutral camera, makes two different types of measurements. It will obtain three-dimensional

distributions, velocities and the rough composition of magnetospheric and interplanetary ions. Principal investigator is Dr. Stamatios M. Krimigis of Johns Hopkins University, Baltimore, MD.

□ **Radio and Plasma Wave Science** instrument will measure electrical and magnetic fields in the plasma of the interplanetary medium and Saturn's magnetosphere, as well as electron density and temperature. Plasma is essentially a soup of free electrons and positively charged ions, the latter being atoms that have lost one or more electrons. Plasma makes up most of the universe and is created by the heating of gases by stars and other bodies in space. Plasma is distributed by the solar wind; it is also "contained" by magnetic fields (that is, the magnetospheres) of bodies such as Saturn and Titan. The major components of the instrument are an electric field sensor, a magnetic search coil assembly and a Langmuir probe. The electric field sensor is made up of three deployable antenna elements mounted on the upper equipment module of the Cassini orbiter. Each element is a collapsible beryllium-copper tube that is rolled up during launch and subsequently unrolled to its 10-meter (about 33-foot) length by a motor drive. The magnetic search coils are mounted on a small platform attached to a support for Cassini's high-gain antenna. The Langmuir probe, which measures electron density and temperature, is a metallic sphere 50 millimeters (about 2 inches) in diameter. The probe is attached to the same platform by a 1-meter (about 3-foot) deployable boom. Principal investigator is Dr. Donald A. Gurnett of the University of Iowa, Iowa City, IA.

### **Huygens Probe Instruments**

The Huygens descent probe contains a total of six science instruments. They are:

□ **Descent Imager/Spectral Radiometer** uses 13 fields of view, operating at wavelengths of 350 to 1700 nanometers, to obtain a variety of imaging and spectral observations. Infrared and visible imagers will observe Titan's surface during the latter stages of the descent. Using the Huygens probe's rotation, the imagers will build a mosaic of pictures around the landing site. A side-looking visible imager will view the horizon and the underside of any cloud deck. The spectral radiometer will measure concentrations of argon and methane in the atmosphere. It also will determine if the local surface is solid or liquid, and, if solid, its topography. Solar aureole sensors will measure the light intensity around the Sun resulting from scattering by particles suspended in the atmosphere, permitting calculations of their size, number and density. Principal investigator is Dr. Martin G. Tomasko of the University of Arizona, Tucson, AZ.

□ **Huygens Atmospheric Structure Instrument** investigates the physical properties of Titan's atmosphere, including temperature, pressure and atmospheric density as a function of altitude, wind gusts and, in the event of a landing on a liquid surface, wave motion. Comprising a variety of sensors, the instrument will also measure the ion and electron conductivity of the atmosphere and search for electromagnetic wave activity. On Titan's surface, the instrument will be able to measure the conductivity of surface material. The instrument also processes the signal from the Huygens probe's radar altimeter to obtain information on surface topography, roughness and electrical properties. Principal investigator is Dr. Marcello Fulchignoni of the Paris Observatory, Meudon, France.

❑ **Aerosol Collector and Pyrolyzer** traps particles suspended in Titan's atmosphere using a deployable sampling device. Samples are heated in ovens to vaporize the ice particles and decompose the complex organic materials into their component chemicals. The products are then passed to the gas chromatograph/mass spectrometer for analysis. The instrument will obtain samples at two altitude ranges. The first sample will be taken at altitudes down to 30 kilometers (about 19 miles) above the surface. The second sample will be obtained at an altitude of about 20 kilometers (about 12 miles). Principal investigator is Dr. Guy M. Israel of the Service d'Aeronomie du Centre National de la Recherche Scientifique, Verrieres-le-Buisson, France.

❑ **Gas Chromatograph/Mass Spectrometer** provides a quantitative analysis of Titan's atmosphere. Atmospheric samples are transferred into the instrument by dynamic pressure as the Huygens probe descends through the atmosphere. The mass spectrometer constructs a spectrum of the molecular masses of the gas driven into the instrument. Just before landing, the instrument's inlet port is heated to vaporize material on contact with the surface. Following a safe landing, the instrument can determine Titan's surface composition. The mass spectrometer serves as the detector for the gas chromatograph, for unseparated atmospheric samples and for samples provided by the aerosol collector and pyrolyzer. Portions of the instrument are identical in design to the Cassini orbiter's ion and neutral mass spectrometer. Principal investigator is Dr. Hasso B. Neimann of NASA's Goddard Space Flight Center, Greenbelt, MD.

❑ **Doppler Wind Experiment** uses two ultrastable oscillators, one on the Huygens probe and one on the Cassini orbiter, to give Huygens' radio relay link a stable carrier frequency. Orbiter measurements of changes in probe frequency caused by Doppler shift will provide information on the probe's motion. In turn, scientists will be able to derive a height profile of the zonal wind (the component of wind along the line of sight) and its turbulence. Principal investigator is Dr. Michael K. Bird of the University of Bonn, Germany.

❑ **Surface Science Package** contains a number of sensors to determine the physical properties and composition of Titan's surface. An acoustic sounder measures the rate of descent, surface roughness and the speed of sound in any liquid. During descent, measurements of the speed of sound will give information on atmospheric composition and temperature. An accelerometer records the deceleration profile at impact, indicating the hardness of the surface. Tilt sensors (liquid-filled tubes with electrodes) measure any pendulum motion of the Huygens probe during descent, indicate the Huygens probe orientation after landing and measure any wave motion. If the surface is liquid, other sensors measure its density, temperature, refractive index, thermal conductivity, heat capacity and electrical properties. A group of platinum resistance wires, through two of which a heating current can be passed, will measure temperature and thermal conductivity of the surface and lower atmosphere and the heat capacity of the surface material. If the probe lands in liquid, a transducer, pointed downward and operating at 15 kilohertz, will conduct an acoustic sounding of the liquid's depth. The instrument will also provide some crude topographic mapping of the surface as the probe descends the last few meters (or yards) through the atmosphere. Principal investigator is Dr. John C. Zarnecki of the University of Kent, England.

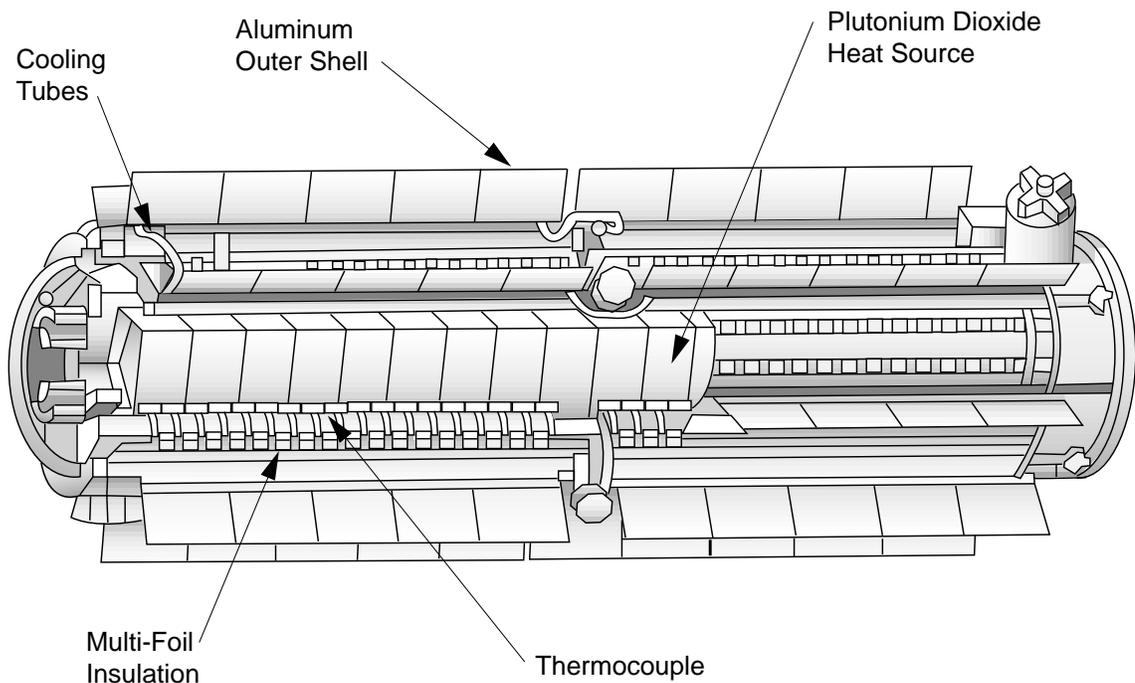
# Cassini's Nuclear Safety

The Cassini spacecraft derives its electrical power from radioisotope thermoelectric generators (RTGs), lightweight, compact spacecraft power systems that are extraordinarily reliable. RTGs are not nuclear reactors and have no moving parts. They use neither fission nor fusion processes to produce energy. Instead, they provide power through the natural radioactive decay of plutonium (mostly Pu-238, a non-weapons-grade isotope). The heat generated by this natural process is changed into electricity by solid-state thermoelectric converters.

RTGs enable spacecraft to operate at significant distances from the Sun or in other areas where solar power systems would not be feasible. They remain unmatched for power output, reliability and durability by any other power source for missions to the outer solar system.

The United States has an outstanding record of safety in using RTGs on 23 missions over the past 30 years. While RTGs have never caused a spacecraft failure on any of these missions, they have been onboard three missions which experienced malfunctions for other reasons. In all cases, the RTGs performed as designed.

More than three decades have been invested in the engineering, safety analysis and testing of RTGs. Safety features are incorporated into the RTG design, and extensive testing has demonstrated that they can withstand physical conditions more severe than those expected from most accidents.



*Radioisotope thermoelectric generator (RTG)*

First, the fuel is in the heat-resistant, ceramic form of plutonium dioxide, which reduces its chance of vaporizing in fire or reentry environments. This ceramic-form fuel is also highly insoluble, has a low chemical reactivity, and primarily fractures into large, non-respirable particles and chunks. These characteristics help to mitigate the potential health effects from accidents involving the release of this fuel.

Second, the fuel in each RTG is divided among 18 small, independent modular units, each with its own heat shield and impact shell. This design reduces the chances of fuel release in an accident because all modules would not be equally impacted in an accident.

Third, multiple layers of protective materials, including iridium capsules and high-strength graphite blocks, are used to protect the fuel and prevent its accidental release. Iridium metal has a very high melting point and is strong, corrosion-resistant and chemically compatible with plutonium dioxide. These characteristics make iridium useful for protecting and containing each fuel pellet. Graphite is used because it is lightweight and highly heat-resistant.

Potential RTG accidents are sometimes mistakenly equated with accidents at nuclear power plants. It is completely inaccurate to associate an RTG accident with Chernobyl or any other past radiation accident involving nuclear fission. RTGs do not use either a fusion or fission process, and could never explode like a nuclear bomb under any accident scenario. Neither could an accident involving an RTG create the kind of radiation sickness associated with nuclear explosions.

NASA and the Department of Energy, the producer of the RTGs, place the highest priority on assuring the safe use of plutonium in space. Thorough and detailed safety analyses are conducted before launching spacecraft with RTGs, and many prudent steps are taken to reduce the risks involved in missions using RTGs. In addition to NASA's internal safety requirements and reviews, NASA missions that carry nuclear material also undergo an extensive external safety review involving detailed testing and analysis. Further, an independent safety evaluation of the Cassini mission has been performed as part of the nuclear launch safety approval process by an Interagency Nuclear Safety Review Panel (INSRP), which is supported by experts from government, industry and academia.

## **Alternatives**

Studies conducted by NASA's Jet Propulsion Laboratory (JPL) have concluded that neither fuel cells nor spacecraft batteries demonstrate the operational life needed for planetary missions, whose duration can exceed 10 years from launch. In addition, the large mass of batteries that would be needed to power a mission such as Cassini exceeds current launch vehicle lift capabilities.

JPL's rigorous analysis has also taken into account the advances in solar power technologies that have occurred over the last decade. The conclusion reached by JPL researchers is that solar technology is still not capable of providing sufficient and reliable electrical power for the Cassini mission. The mass of solar arrays required would make the spacecraft too heavy for

available launch vehicles. Even if a sufficiently powerful launch vehicle were available for an all-solar Cassini, other limitations exist with current and near-term solar technologies.

The behavior of solar cells at vast distances from the Sun is not well understood and would add significant risk to the success of a solar-powered mission to Saturn. Saturn is located approximately 1.42 billion kilometers (882 million miles) from the Sun, nearly twice as far from the Sun as Jupiter, the next closest planet.

The size of solar arrays that would be needed, about the size of two tennis courts, would not only be difficult to deploy reliably, but would make turns and other critical maneuvers extraordinarily difficult to perform. This would severely inhibit Cassini's ability to achieve its science objectives.

The large arrays would seriously interfere with the fields of view of many of the science experiments and navigation sensors, further limiting the Cassini mission's ability to achieve the science objectives.

Large arrays could generate serious electromagnetic and electrostatic interference, which would adversely impact the operation of the science experiments and the Cassini spacecraft's communications equipment and computers.

### **Cassini's Earth Swingby**

By aiming a spacecraft so that it passes close to a planet or moon, it is possible to boost the spacecraft on to still more distant destinations with greater velocity. This gravity-assist maneuver has become an established method of launching massive, instrument-laden spacecraft to the outer planets. Cassini will make use of this technique when it swings by Venus twice, then the Earth and Jupiter to reach its ultimate destination of Saturn.

The Earth swingby does not represent a substantial risk to Earth's population because the probability of a reentry during the maneuver is extremely low, less than one in one million. NASA's robotic planetary spacecraft have performed numerous similar maneuvers with extraordinary precision. The redundant design of Cassini's systems and navigational capability allows control of the swingby altitude at Earth to within an accuracy of 3 to 5 kilometers (2 to 3 miles) at an altitude of 800 kilometers (500 miles) or higher.

In addition, NASA has taken specific actions to design the spacecraft and mission in such a way as to ensure the probability of Earth impact is less than one in one million. For example, until seven days before the Earth swingby, the spacecraft is on a trajectory that, without any further maneuvers, would miss the Earth by thousands of kilometers. This trajectory strictly limits the possibility that random external events, such as a micrometeoroid puncture of a spacecraft propellant tank, might lead to Earth impact.

## **Radiation Hazards of Plutonium-238**

Plutonium-238 gives off short-range alpha particles, helium nuclei that usually travel no more than about three inches in air. While the fuel is contained within its iridium capsule, the alpha radiation does not present a hazard, and the external dose resulting from the low levels of gamma and neutron radiation associated with the plutonium dioxide RTG fuel generally do not represent a significant health hazard. External alpha radiation would be stopped by clothing, an outer layer of unbroken skin, or even a sheet of paper. The point at which Pu-238 can become a health hazard is when it is deposited into the body in tiny particle form and becomes lodged there.

If an individual were to inhale plutonium dioxide particles of a sufficiently small size to be deposited and retained in proximity to lung tissue, the alpha radiation could lead to forms of cancer. The ceramic form of plutonium used in RTGs, however, is made to inhibit the fuel from shattering into fine particles that could be readily inhaled.

The ceramic form of plutonium dioxide fuel also has low solubility in water, so it has little potential to migrate in groundwater or be taken up by plants. Plutonium dioxide also is highly insoluble in the human digestive system.

A common misconception is that a small amount of plutonium, such as one pound, if evenly distributed over the entire world, could induce lung cancer in every person on Earth. While plutonium can alter or kill living cells if deposited directly onto sensitive human tissue, the important point is that it must be in a form that enables environmental transport and intake by humans. Research has demonstrated that the mechanisms of plutonium dispersion into and transport through the environment, and hence into humans, are extremely difficult and inefficient.

Even in the highly unlikely release of plutonium dioxide from Cassini's RTGs in the event of an accident, independently reviewed analysis shows that the radiation hazard to the average exposed individual would be minuscule, about 1/15,000 of the lifetime exposure a person receives from natural radiation sources.

# The International Team

The Cassini program is an international cooperative effort involving NASA, the European Space Agency (ESA) and the Italian Space Agency, Agenzia Spaziale Italiana (ASI), as well as several separate European academic and industrial contributors. The Cassini partnership represents an undertaking whose scope and cost would not likely be borne by any single nation, but it made possible through shared investment and participation. Hundreds of scientists and engineers from 16 European countries and 33 U.S. states make up team that developed and will fly and receive data from Cassini and Huygens.

In the United States, the mission is managed for NASA's Office of Space Science by the Jet Propulsion Laboratory (JPL), Pasadena, CA. JPL is a division of the California Institute of Technology. At JPL, Richard J. Spehalski is the Cassini program manager, and Ronald F. Draper is the deputy program manager. Dr. Dennis L. Matson is the Cassini project scientist and Dr. Linda J. Spilker is the deputy project scientist. Thomas R. Gavin is spacecraft system manager, William G. Fawcett is science instruments manager, Charles E. Kohlhasse is science and mission design manager, and Peter E. Doms is mission and science operations manager.

At NASA Headquarters, Mark Dahl is Cassini program executive and Henry C. Brinton is Cassini program scientist.

The major U.S. contractor is Lockheed Martin, whose contributions include the launch vehicle and upper stage, spacecraft propulsion module and the radioisotope thermoelectric generators. NASA's Lewis Research Center managed development of the Centaur upper stage.

Development of the Huygens Titan probe is managed by the European Space Technology and Research Center (ESTEC). ESTEC's prime contractor, Aerospatiale in Toulouse, France, assembled the probe with equipment supplied by many European countries. Huygens' batteries and two scientific instruments came from the United States. At ESA, Hamid Hassan is Huygens project manager, and Dr. Jean-Pierre Lebreton is project scientist.

At ASI, Enrico Flamini is the project manager for Cassini's radio antenna and other contributions to the spacecraft.

The U.S. Department of Energy provided Cassini's radioisotope thermoelectric generators. Beverly Cook is program manager for radioisotope power systems at DOE's Office of Space Power Systems, Germantown, MD.

The U.S. Air Force provided the Titan IV/Centaur launch vehicle. Launch operations are managed by the 45th Space Wing, Cape Canaveral, FL, under the command of Brig. Gen. Randy Starbuck.