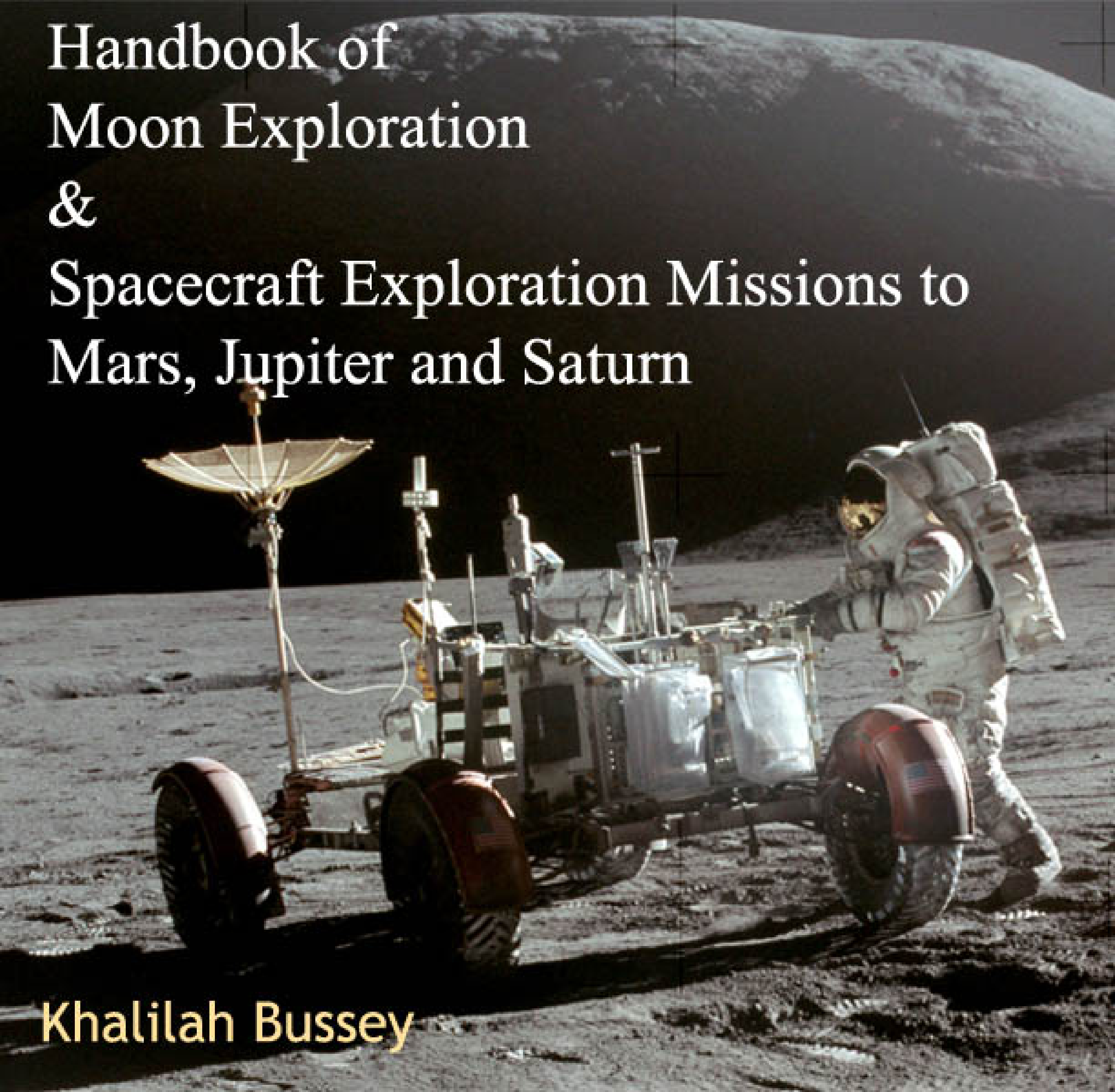
Handbook of Moon Exploration & Spacecraft Exploration Missions to Mars, Jupiter and Saturn



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Chandrayaan-2

Chandrayaan-2

Operator	Indian Space Research Organisation, Russian Federal Space Agency
Mission type	Orbiter, lander and one rover
Satellite of	Moon
Launch date	2013 (expected)
Launch vehicle	GSLV
Mission duration	One year (orbiter and rover)
Homepage	ISRO
Mass	2,650 Kg (orbiter, lander and rover)

Chandrayaan-2, is a joint lunar exploration mission proposed by the Indian Space Research Organisation (ISRO) and the Russian Federal Space Agency (RKA) and has a projected cost of ₹425 crore (US$90 million). The mission, proposed to be launched in 2013 by a Geosynchronous Satellite Launch Vehicle (GSLV) launch vehicle, includes a lunar orbiter and a lunar rover made in India as well as one lander built by Russia. According to ISRO, this mission will use and test various new technologies and conduct 'new' experiments. The wheeled rover will move on the lunar surface and will pick up soil or rock samples for on-site chemical analysis. The data will be sent to Earth through the Chandrayaan-2 orbiter. The team headed by Mylswamy Annadurai that was behind the success of the Chandrayaan-1 mission, is working on Chandrayaan-2.

History

The Indian Government approved the mission in a meeting of the Union Cabinet held on 18 September 2008 chaired by Prime Minister Manmohan Singh.

On November 12, 2007, representatives of the Russian Federal Space Agency (Roskosmos) and ISRO signed an agreement for the two agencies to work together on the Chandrayaan-2 project. ISRO will have the prime responsibility for the orbiter and rover, while Roskosmos will be responsible for the lander. The design of the space craft was completed in August 2009, with scientists of both countries conducting a joint review.

Design

Space craft

The mission is planned to fly on a Geosynchronous Satellite Launch Vehicle Mk-II (GSLV) with an approximate lift-off weight of 2,650 kg from Satish Dhawan Space Center on Sriharikota Island.

Orbiter

ISRO will design the orbiter, which will orbit the Moon at an altitude of 200km. It is decided that the mission would carry five payloads on the orbiter. Three of the payloads are new, while two others are improved versions of those flown on Chandrayaan-1 orbiter. The approximate launch mass will be 1,400 kg.

Lander

Unlike Chandrayaan-1's lunar probe, which impacted the Moon's surface, the lander will make a soft landing. The Russian Federal Space Agency will provide the lander. The approximate weight of the lander and rover is 1,250 kg. The Russian space agency Roscosmos plans to test the lander in 2011.

Rover

The rover will weigh 30-100 kg and will operate on solar power. The rover will move on wheels on the lunar surface, pick up samples of soil or rocks, perform chemical analysis and send the data to the orbiter above, which will relay it to the Earth station.

Payload

ISRO has announced that an expert committee has decided on five payloads for the orbiter, and two for the rover. While it was initially reported that NASA and ESA would participate in the mission by providing some scientific instruments for the orbiter, ISRO has later clarified that due to weight restrictions it will not be carrying foreign payloads on this mission.

Orbiter payload

- Large Area Soft X-ray Spectrometer (CLASS) from ISRO Satellite Centre (ISAC), Bangalore and Solar X-ray monitor (XSM) from Physical Research Laboratory (PRL), Ahmedabad for mapping major elements present on the lunar surface.

- L and S band Synthetic Aperture Radar (SAR) from Space Applications Centre (SAC), Ahmedabad for probing the first few tens of metres of the lunar surface for the presence of different constituents, including water ice. SAR is expected to provide further evidence confirming the presence of water ice below the shadowed regions of the Moon.

- Imaging IR Spectrometer (IIRS) from SAC, Ahmedabad for mapping of lunar surface over a wide wavelength range for the study of minerals, water molecules and hydroxyl present.

- Neutral Mass Spectrometer (ChACE-2) from Space Physics Laboratory (SPL), Thiruvananthapuram to carry out a detailed study of the lunar exosphere.

- Terrain Mapping Camera-2 (TMC-2) from SAC, Ahmedabad for preparing a three-dimensional map essential for studying the lunar mineralogy and geology.

Rover payload

- Laser induced Breakdown Spectroscope (LIBS) from Laboratory for Electro Optic Systems (LEOS), Bangalore.

- Alpha Particle Induced X-ray Spectroscope (APIXS) from PRL, Ahmedabad.

Current status

As of 30 August 2010, ISRO has finalized payloads for Chandrayaan-2 mission.

Chapter- 2

Luna-Glob & Gravity Recovery and Interior Laboratory

Luna-Glob

Luna-Glob (Russian: **Луна-Глоб**, meaning "Lunar sphere") is the name of a Moon-exploration program by the Russian Federal Space Agency (Roscosmos) based on plans dating back to 1997. Due to financial problems, however, the project was put on hold only to be revived a few years later. Initially scheduled for launch in 2012, the mission has been brought forward twice, first to 2010 and then to 2009. However, as of late 2008, the plan is again to meet the original 2012 launch date.

Luna-Glob is the first of four missions planned before the creation of a fully robotic lunar base scheduled for after 2015.

Luna-Glob 1

Luna-Glob 1

Operator	Roscosmos
Mission type	Orbiter, lander, penetrators
Satellite of	**Moon**
Launch date	2012
Launch vehicle	Soyuz 2 rocket
Mass	launch mass of 7.24 tonnes, orbiter payload mass is 120 kg

Luna-Glob 1 is an unmanned mission to the Moon planned by Russia including an orbiter with ground penetrating sensors. Four Japanese-built penetrators inherited from the Lunar-A will be used, each weighing 45 kg (100 lb), including 14 kg (31 lb) for the penetrator proper.

Luna-Glob is slated to be launched in 2012 by a Soyuz 2 rocket Furthermore, seismic experiments are planned, including the use of 4 penetrators, which will slam into the lunar surface equipped to detect seismic signals. These experiments are expected to help clarify the origin of Earth's moon whereas two of the penetrators are planned to land near the Apollo 11 and Apollo 12 landing sites, taking advantage of seismic data gathered there from 1969 to 1974.

The payload of the orbiter will total 120 kg and include astrophysics experiments, dust monitors, plasma sensors, including the LORD astronomy payload, designed to study ultra-high-energy cosmic rays.

Luna-Glob 2

Luna-Glob 2

Operator	Roscosmos, ISRO
Mission type	Landing module, moon rover
Launch date	2013
Launch vehicle	GSLV
Mission duration	1 year
Mass	1,000 kg total, 50 kg rover

The Luna-Glob 2 joint orbiter-rover mission (the orbiter will be the Indian Chandrayaan-2) is planned for 2013 and will feature a 58 kg Russian Polar Moon Rover and lander, as part of the International Lunar Network. This mission will land in Moon's south pole, examine a crater and operate for up to one year. The six wheeled, solar powered rover will land near one of the poles and will survive for a year, roving up to 150 km at a speed of 360 m/h.

Luna-Grunt

Luna-Grunt

Operator	Roscosmos
Mission type	Landing vehicles, moon rover and moon ascent vehicle (sample return)
Launch date	2014 and 2015

Launch vehicle	Soyuz-Fregate rocket
Mass	400 kg (880 lb) (rover), 400 kg (ascent stage), up to 1 kg of moon soil returned

The next two missions, to be called Luna-Grunt, will launch in 2014, featuring an orbiter and a lander. The lander carries a large 400 kg rover capable of in-situ soil analysis. Later, in 2015, a second lander with a 400 kg ascent stage will return up to 1 kg of surface and rock samples.

Robotic lunar base

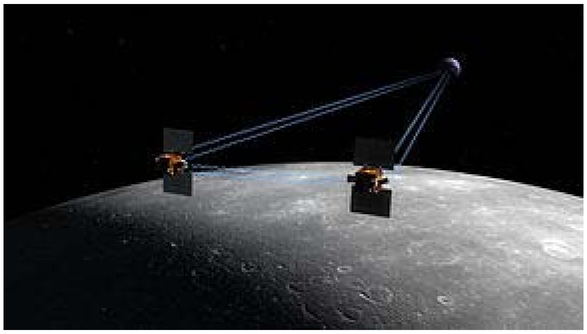
The Lunnyj Poligon robotic lunar base that follows Glob and Grunt would be a "Robotic proving ground", consist of several components:

- solar power station,
- telecommunication station
- technological station
- scientific station
- long-range research rover
- landing and launch area
- orbiting satellite

This project is planned for 2020, with an expected completion date of 2037.

Gravity Recovery and Interior Laboratory

Gravity Recovery and Interior Laboratory



Artist's interpretation of the GRAIL tandem spacecraft above the lunar surface

Operator	NASA / JPL
Major contractors	Lockheed Martin Space Systems Massachusetts Institute of Technology
Mission type	Orbiter
Satellite of	Moon
Orbital insertion date	January 2012 (planned)
Launch date	2011-09-08 (planned)
Launch vehicle	Delta II
Launch site	Space Launch Complex 17B Cape Canaveral Air Force Station
Mission duration	March 2012 - May 2012 (planned)
COSPAR ID	GRAIL
Mass	132.6 kg (292 lb)
Power	(Solar array / Li-ion battery)

The **Gravity Recovery and Interior Laboratory** (**GRAIL**) mission is a Discovery Program mission which will use high-quality gravitational field mapping of the Moon to determine its interior structure. Maria Zuber of the Massachusetts Institute of Technology is GRAIL's principal investigator. NASA's Jet Propulsion Laboratory will manage the project.

The gravity mapping technique is similar to that used by Gravity Recovery and Climate Experiment (GRACE), and the spacecraft design is based on XSS-11.

GRAIL is scheduled for launch on 8 September 2011 aboard a Delta II launch vehicle.

Objectives

The GRAIL mission consists of two spacecraft in a polar orbit around the moon. Each spacecraft transmits and receives telemetry from the other spacecraft and Earth-based facilities. By measuring the change in distance between the two spacecraft, the gravity field and geological structure of the moon can be obtained.

Primary objectives

- Determine structure of the lunar crust and lithosphere
- Asymmetric thermal evolution of the moon
- Subsurface structure of impact basins and origin of mascons
- Brecciation and magmatism
- Deep interior structure
- Detection of inner core

Instruments

- K_a band ranging assembly (KBR)
- Radio science beacon (RSB)
- MoonKam (Moon Knowledge Acquired by Middle school students)

Chapter- 3

Lunar Atmosphere and Dust Environment Explorer, International Lunar Network & Chang'e 3

Lunar Atmosphere and Dust Environment Explorer

Lunar Atmosphere and Dust Environment Explorer

Artist's interpretation of the LADEE spacecraft

Operator	NASA
Mission type	Orbiter
Satellite of	The Moon
Launch date	2013-05-01 00:00:00 UTC
Carrier rocket	Minotaur V
Launch site	Wallops Flight Facility Wallops Island, Virginia
Mission duration	100 days nominal, up to 9 months expected
COSPAR ID	LADEE

Mass	330 kg
Power	100 W
	Orbital elements
Eccentricity	Near-circular
Inclination	Retrograde equatorial orbit
Altitude	50 km
Orbital period	113 minutes

The **Lunar Atmosphere and Dust Environment Explorer** (**LADEE**) is a space exploration mission scheduled for launch on 1 May 2012. To carry out the mission NASA will send a robotic spacecraft into orbit around the Moon, and use instruments aboard the spacecraft to study the Moon's atmosphere and dust in the Moon's vicinity. Instruments will include a dust detector, a neutral mass spectrometer, an ultraviolet-visible spectrometer, and recently announced, a laser communications (lasercomm) terminal. LADEE was announced during the presentation of NASA's FY09 budget in February 2008. It will be launched aboard a Minotaur V from the Mid-Atlantic Regional Spaceport.

Mission objectives

LADEE is a strategic mission that will address three major science goals:

- Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity;
- Determine if the Apollo astronaut sightings of diffuse emission at 10s of km above the surface were Na glow or dust and;
- Document the dust impactor environment (size-frequency) to help guide design engineering for the outpost and also future robotic missions.

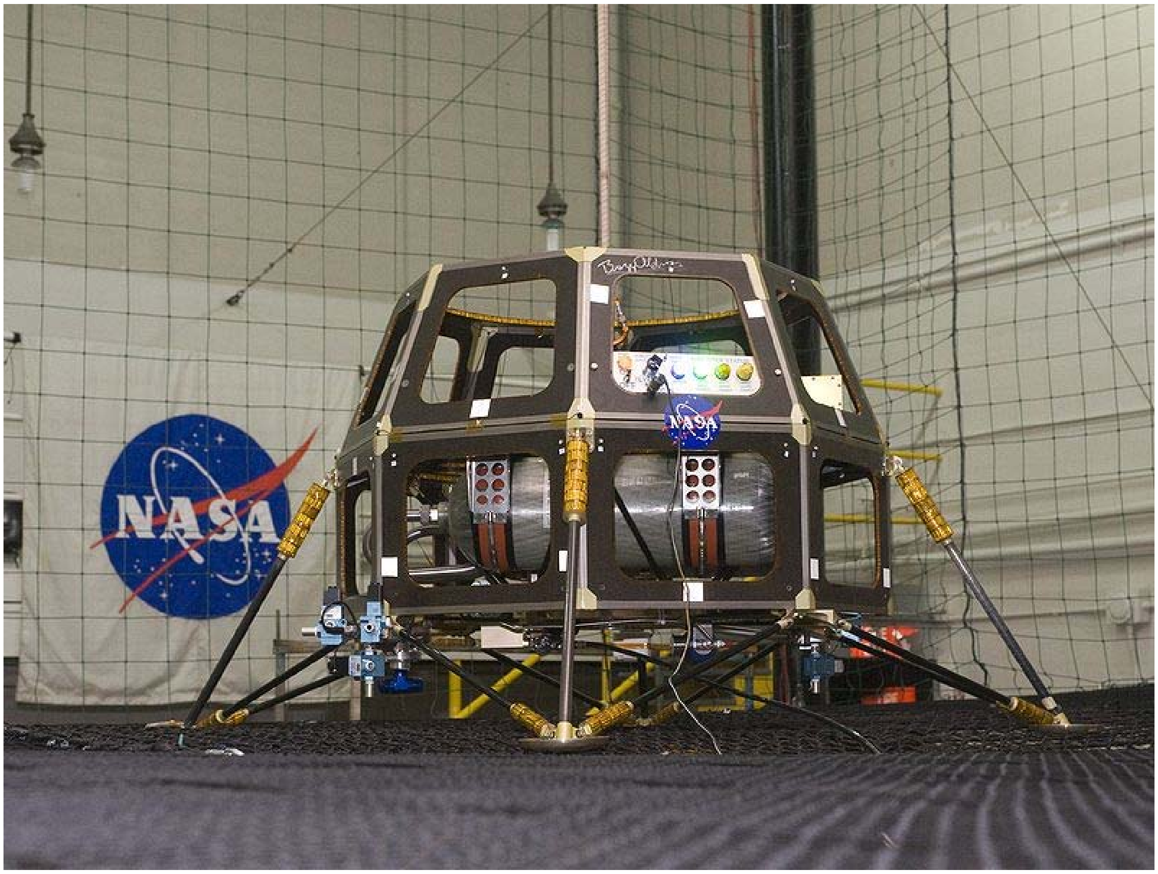
Launch

LADEE is scheduled for launch on 1 May 2012 out of the Wallops Flight Facility on a Minotaur V carrier rocket.

Propulsion system

The LADEE propulsion system will consist of an orbit control system (OCS) and a reaction control system (RCS). The OCS will provide velocity control along the +Z axis for large velocity adjustments. The RCS will provide three-axis attitude control during burns of the OCS system, and will also provide momentum dumps for the reaction wheels which are the primary attitude control system between OCS burns.

The LADEE spacecraft, as conceived in August 2009.



The Modular Common Spacecraft Bus that will become LADEE, being tested at NASA Ames Research Center in 2008.

International Lunar Network

The **International Lunar Network** or **ILN** is a proposed network of a series of landed stations of the United States and the other space-faring countries on the lunar surface in the 2010s. Each of these stations will act as a node in a lunar geophysical network. Ultimately this network could comprise 8-10 or more nodes operating simultaneously. In the ILN concept, each node will have a minimum of two core capabilities. These capabilities include seismic sensing, heat flow sensing, and laser retroreflectors, and will be specific to each station. Because some nodes are planned to be located on the far side of the Moon, NASA will study a lunar communications relay satellite capability as a part of its contribution to this project.

Individual nodes launched by different space agencies can and likely will carry additional, unique experiments to study local or global lunar science. Such experiments might include atmospheric and dust instruments, plasma physics investigations, astronomical instruments, electromagnetic profiling of lunar regolith and crust, local geochemistry, and in-situ resource utilization demonstrations.

On July 24, 2008 a meeting of the space agencies of Canada, France, Germany, India, Italy, Japan, the Republic of Korea, the United Kingdom, and the United States was held at NASA's Lunar Science Institute, located at the Ames Research Center. During the meeting, the representatives of the nine space agencies discussed about the cooperation on ILN and agreed on a statement of intent as a first step in planning. NASA’s Science Mission Directorate (SMD) and Exploration Systems Mission Directorate (ESMD) have agreed to provide two pairs of nodes (landed stations) for this network. The first two nodes will be launched in 2013 and 2014. The landers are being developed under the Lunar Precursor Robotic Program at NASA's Marshall Space Flight Center in Huntsville, Alabama. The second pair of nodes would be launched in 2016-2017.

Chang'e 3

Chang'e 3

Operator	CNSA
Mission type	Orbiter, lander and one rover
Satellite of	The Moon
Launch date	2013
Mass	3,750-kg. (8,250-lb.)

Chang'e 3 is a Chinese lunar-lander and rover scheduled for launch in 2013. It will be China's first lunar rover, part of the second phase of the Chinese lunar exploration program undertaken by the China National Space Administration (CNSA).

In 2009, the 2013 launch date was confirmed for a landing craft and rover. It will use variable thrusters to make a vertical landing on the surface. At that time, the stated target for the lander was near the moon's equator. The rover will leave Chang'e 3 and work on the surface for three months. Energy will be provided by radioisotope thermoelectric generator so that the rover can operate through lunar nights.

A six-wheeled lunar vehicle has been under development since 2002 at the Shanghai Aerospace System Engineering Institute, where a specialized testing laboratory has been outfitted to replicate the lunar surface. The 1.5 meter high, 120 kg (with 20 kg payload) rover has completed assembly by May 2010, and is designed to transmit video in real time, and dig and analyze soil samples. With an average speed of 100 meters/hour, it can negotiate inclines and has automatic sensors to prevent it from crashing into other objects.

Chang'e 3 is scheduled to land at Sinus Iridum, a plain of basaltic lava that forms a northwestern extension to the Mare Imbrium. Since Sinus Iridum has a latitude of 44 degrees north it contradicts the previously stated equatorial site.

Chapter- 4

Chinese Lunar Exploration Program

中国探月
CLEP

Insignia of the program

Chinese Lunar Exploration Program (**CLEP**) (simplified Chinese: 中国探月; traditional Chinese: 中國探月; pinyin: *Zhōngguó Tànyuè*) also known as **Chang'e program** is a program of robotic explorations and human missions to the Moon undertaken by China National Space Administration (CNSA), People's Republic of China's space agency. It uses Chang'e lunar orbiters, rovers and soil return spacecraft and adapted Long March 3A, Long March 5/E and Long March 7 launch vehicles. The launch and the flight are monitored constantly by a TT&C System (Deep Space Tracking Network, with radio antennas of 50 m in Beijing, 40 m in Kunming, Shanghai and Ürümqi, forming a 3000 km VLBI antenna.) and the Ground Application System, responsible for downlink data reception.

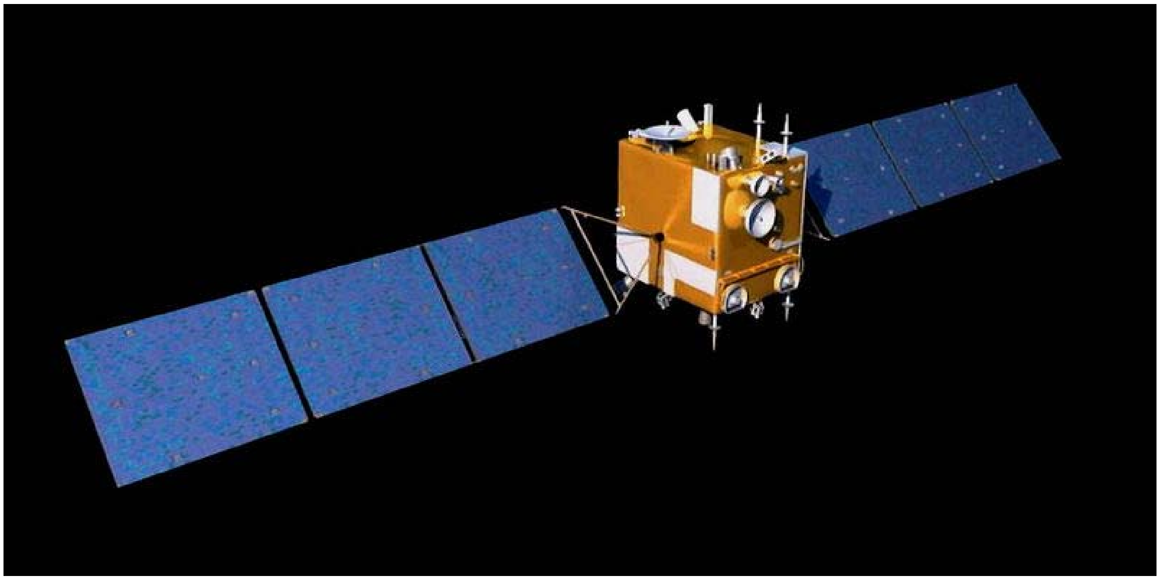
The first spacecraft of the program, Chang'e 1, an un-manned lunar orbiter was successfully launched at Xichang Satellite Launch Center on October 24, 2007 (delayed from 17–19 April 2007).

Ouyang Ziyuan, one of the most prominent Chinese experts in geological research on underground nuclear testing and extraterrestrial materials, was the first to advocate not only the exploitation of the known huge lunar reserves of metals such as iron, but also the mining of lunar helium-3 as an ideal fuel for nuclear fusion power plants. He is now in charge of the Chang'e program. He is known to be one of the strongest supporters of the Chinese human lunar exploration program, and is currently serving as the chief scientist of the program. Another prominent Chinese scientist, Sun Jiadong, was assigned as the general designer, while a younger scientist Sun Zezhou (孙泽州, unrelated to Sun Jiadong) was assigned as the deputy general designer. The program manager was Luan Enjie (栾恩杰).

Program structure

According to CNSA, the program will go through three phases :

Phase I : Orbital mission (Chang'e 1 & 2)



Chang'e 2 spacecraft.

The first phase of the exploration program starts with the launch of two lunar orbiters.

- Chang'e 1 was the first to be successfully launched as scheduled on October 24, 2007.
- Chang'e 2 was launched on October 1, 2010.

Phase II : Soft lander (Chang'e 3)

In the second phase of the lunar exploration program, two lunar landers will be launched to deploy moon rovers for surface exploration in a limited area. These missions were originally planned for 2012 requiring the use of the CZ-5/E heavy launch vehicle.

Currently, the second and third phases of the program will both require the availability of the heavy-lift Long March 5 (CZ-5) booster. Huang Chunping, the former head of rocket science at China's manned space program, told Xinhua news agency in March 2007 that the Long March 5 (CZ-5) rocket would be ready for launch 'in seven or eight years', which implied that CZ-5 would not be used in the second phase of the Chang'e program. The Hainan Spaceport, fourth and southernmost space center, will be upgraded to suit the new CZ-5 Heavy ELV. It has also been reported that the second phase might use a CZ-3B rocket instead.

It is said that the second phase of the program would include the launch of at least two landers, that will carry small remote-controlled Moon rovers to conduct an inspection of the moon's surface and probe the moon's resources. It would also provide data to determine the selection of a moon base.

On December 14, 2005, many aspects of the above information were confirmed, when it was reported "an effort to launch lunar orbiting satellites will be supplanted in 2007 by a program aimed at accomplishing an unmanned lunar landing. A program to return unmanned space vehicles from the moon will begin in 2012 and last for five years, until the manned program gets underway" in 2017.

A six-wheeled lunar vehicle has been under development since 2002 at the Shanghai Aerospace System Engineering Institute where a specialized testing laboratory has been outfitted to replicate the lunar surface. The 1.5-meter high, 200-kilogram rover is designed to transmit video in real time, dig and analyze soil samples. With an average speed of 100 meters/hour, it can negotiate inclines and has automatic sensors to prevent it from crashing into other objects.

In late 2008, Chen Qiufa (deputy Minister of MIIT and head of SASTIND) indicated that Chang’e 3 Lunar Rover would launch in late 2011 on a Long March 3B rocket. The rover will conduct studies of the Moon’s geology, topography, and mineral and chemical composition.

In 2009, the 2013 launch date was confirmed, for a landing craft and rover called Chang'e-3. It will use variable thrusters to make a vertical landing on the surface near the moon's equator area. The lunar rover will leave Chang'e-3 and work on the surface for three months. Energy will be provided by radioisotope thermoelectric generator so that the rover survives lunar nights.

Phase III : Automated sample return (Chang'e 4)

The third phase of the lunar exploration program is planned for 2017 with the use of the CZ-5/E heavy launch vehicle. On the basis of the lander mission, a lunar sample return mission will be undertaken, with up to two kilograms of lunar samples returned to Earth.

After that a manned lunar landing might be possible in 2025–2030.

Key technologies (phase I)

Orbit design and flight sequence control

Under the condition of three-body movement of the earth, the moon and its satellite, the orbit design of lunar exploration satellite is more complicated than that of the previous earth satellite. The lunar satellite will be sent into the highly elliptical earth orbit atop a launch vehicle first. After separating from the launch vehicle it will enter into the earth-moon transfer orbit through three accelerations in the phase-modulated orbit (16h, 24h, 48h) by its own propulsion system, during which it needs to carry out several orbit adjustments and attitude maneuvers so as to ensure to be captured by lunar gravity. After operating in the earth-moon orbit for 4–5 days, it will enter into the lunar acquisition orbit. Then, it will enter into the target lunar orbit and carry out pre-designed missions after three brakings and experiencing three different orbit phases.

The three-vector control problem of the lunar satellite's attitude control

During the flight orbiting the moon the satellite should be always oriented to the earth, the moon and the sun: all the onboard detectors should be kept facing the lunar surface to complete the scientific exploration missions; the transmitting/receiving antennas should be maintained facing the earth to receive the commands from the earth and transfer scientific data to the earth for the ground application research; the solar panels should be oriented to the sun to acquire the power for normal operation. During the flight orbiting the moon, the three bodies of the earth, the moon and the sun rotate relatively, so the attitude control is a three-vector control process.

The satellite environment adaptability design

The complexity of the space environment during the satellite operation has higher requirements of the environment adaptability and reliability for the satellite and its instruments. For instance, the strong radiation environment in the earth-moon space will exert great effect on the electronics; the temperature change ranges greatly from 130℃ of the side facing the sun to -170℃ of the side back to the sun, so it has stricter requirements of temperature control for the detectors.

Long-range TT&C and communication

The biggest challenge in the Phase I of the Lunar Exploration Program is TT&C system (Telemetry, Tracking and Command), because its transmission capability must have such a long range. China's previous satellite telemetry has a range of as much as 80,000 km, but the distance between the moon and the earth is about 400,000 km, which brings up new challenge to the TT&C system. In addition, the lunar satellite must carry out many attitude maneuvers during its flight to the moon and during operations orbiting the moon. The distance from east to west in China is only 5,000 km, which is also a challenge to TT&C continuity. China hasn't set up a deep space TT&C network. At present, the combination of space TT&C network and astronomical observation network can meet the basic needs of TT&C, but with a small margin.

Russian cooperation

Anatoly Perminov, head of the Russian Federal Space Agency revealed in September 2006 in RIA Novosti that the two countries were indeed working on the Moon as partners, and that the Russian-Chinese space sub-commission's priority was to conclude a joint Moon exploration agreement by the end of that year.

Chapter- 5

Luna 1 & Luna 3

Luna 1

Luna 1 (Mechta)

Operator	Soviet Union
Major contractors	OKB-1
Mission type	Planetary Science
Satellite of	Sun
Orbits	37 (as of 2005)

Launch date	2 January 1959 at 16:41:21 UTC
Launch vehicle	SS-6/R-7 (8K72)
Mission highlight	Fly-by of Moon on 4 January 1959 at distance of 5,995 km
COSPAR ID	1959-012A
Homepage	NASA NSSDC Master Catalog
Mass	361 kg
Orbital elements	
Semimajor axis	1.146 AU
Eccentricity	0.14767
Inclination	0.01°
Apoapsis	1.315 AU
Periapsis	0.9766 AU
Orbital period	450 d
Lunar landing	
Date	None
Instruments	
Magnetometer (magnetic fields)	
Geiger counter (radiation environment)	
Micrometeoroid detector	
Scintillation counter (magnetospheric studies)	

Luna 1 (E-1 series), first known as *First Cosmic Ship*, then known as **Mechta** (Russian: Мечта, *lit.*: *Dream*) was the first spacecraft to reach the vicinity of the Moon and the first of the Luna program of Soviet automatic interplanetary stations successfully launched in the direction of the Moon.

While traveling through the outer Van Allen radiation belt, the spacecraft's scintillator made observations indicating that a small number of high energy particles exist in the outer belt. The measurements obtained during this mission provided new data on the Earth's radiation belt and outer space. The Moon was found to have no detectable magnetic field. The first ever direct observations and measurements of the solar wind, a strong flow of ionized plasma emanating from the Sun and streaming through interplanetary space, were performed. That ionized plasma concentration was measured to be some 700 particles per cm^3 at altitudes 20-25 thousand km and 300 to 400 particles per cm^3 at altitudes 100-150 thousand km. The spacecraft also marked the first instance of radio communication at the half-million-kilometer distance.

A malfunction in the ground-based control system caused an error in the rocket's burntime, and the spacecraft missed the target and flew by the Moon at a distance of 5,900 km at the closest point. Luna 1 then became the first man-made object to reach heliocentric orbit and was then dubbed a "new planet" and renamed *Mechta*. Its orbit lies between those of Earth and Mars. The name "Luna-1" was applied retroactively years later. Luna-1 was originally referred to as the "First Cosmic Rocket", in reference to its achievement of escape velocity.

The spacecraft

The scientific equipment and the satellite's power center were located in the spherical container, combining for a mass of 361.3 kg. Five antennae extended from one hemisphere. Instrument ports also protruded from the surface of the sphere. The spacecraft contained radio equipment, a tracking transmitter, a telemetry system, five different sets of scientific devices for studying interplanetary space (including a magnetometer, Geiger counter, scintillation counter, and micrometeorite detector), and other equipment. The total final (with fuel spent) mass of the third (upper) stage rocket with the spacecraft was 1472 kg.

It was intended that after a completion of its scientific mission of in-flight measurements, Luna-1 would crash into the Moon, delivering two metallic pennants with the Soviet coat of arms that were included into its package.

The flight

Luna 1 was launched 2 January 1959 at 16:41 GMT (19:41 Moscow Time) from the Baikonur Cosmodrome by a Luna 8K72 rocket.

Luna 1 became the first ever man-made object to reach the escape velocity of the Earth (what is also known as the *second cosmic velocity*), when it separated from its 1472 kg third stage. The third stage, 5.2m long and 2.4m in diameter, traveled along with Luna 1. On 3 January, 3:56:20 Moscow Time, at a distance of 119,500 km from Earth, a large (1 kg) cloud of sodium gas was released by the spacecraft, thus making this probe also the first artificial comet. This glowing orange trail of gas, visible over the Indian Ocean with the brightness of a sixth-magnitude star for a few minutes, was photographed by Mstislav Gnevyshev at the Mountain Station of the Main Astronomical Observatory of the Academy of Sciences of the USSR near Kislovodsk. It served as an experiment on the behavior of gas in outer space. Luna 1 passed within 5995 km of the Moon's surface on 4 January after 34 hours of flight. It went into orbit around the Sun, between the orbits of Earth and Mars.

Luna 3

Luna 3

Luna 3

Operator	Soviet Union
Major contractors	OKB-1
Mission type	Planetary Science Lunar Flyby
Satellite of	Earth
Orbits	~14
Launch date	October 4, 1959 at 00:43:39.7 UTC
Launch vehicle	SS-6/R-7 (8K72)
Mission duration	~207 days
Mission highlight	Lunar flyby on 6 October 1959, 14:16 UTC at distance of 6,200 km over the lunar south pole
COSPAR ID	1959-008A
Homepage	NASA NSSDC Master Catalog
Mass	278.5 kg
Orbital elements	
Semimajor axis	250,682 km

Eccentricity	0.8379
Inclination	76.8°
Apoapsis	460,725 km
Periapsis	40,638 km
Orbital period	15 days

Instruments

Yenisey-2 Camera/Film processor (Lunar photography)

The Soviet space probe **Luna 3** of 1959 (of the E-3 series) was the third space probe to be sent to the neighborhood of the Moon, and this mission was an early feat in the spaceborne exploration of outer space. Though it returned rather poor pictures by later standards, the historic, never-before-seen views of the far side of the Moon caused excitement and interest when they were published around the world, and a tentative *Atlas of the Far Side of the Moon* was created after image processing improved the pictures. This space probe has been commonly called "Lunik 3", predominantly in the Western world.

These views showed mountainous terrain, very different from the near side, and only two dark, low-lying regions which were named Mare Moscovrae (Sea of Moscow) and Mare Desiderii (Sea of Desire). Mare Luna Desiderii was later found to be composed of a smaller mare, Mare Ingenii (Sea of Ingenuity), and several other dark craters.

Design

The space probe was a cylindric canister with hemispheric ends and a wide flange near the top. The probe was 130 cm long and 120 cm at its maximum diameter at the flange. Most of the cylindric section was roughly 95 cm in diameter. The canister was hermetically-sealed and pressurized to about 0.22 atmosphere (23 kilopascals). Several solar cells were mounted on the outside of the cylinder, and these provided electric power to the storage batteries inside the space probe.

Shutters for thermal control were positioned along the cylinder and opened to expose a radiating surface when the internal temperature exceeded 25 celsius. The upper hemisphere of the probe held the covered opening for the cameras. Four antennas protruded from the top of the probe and two from its bottom. Other scientific equipment was mounted on the outside, including micrometeoroid and cosmic ray detectors, and the Yenisey-2 imaging system. The gas jets for its attitude control system were mounted on the lower end of the spacecraft. Several photoelectric cells helped maintain orientation with respect to the Sun and the Moon.

There were no rocket motors for course corrections.

Its interior held the cameras and the photographic film processing system, radio transmitter, storage batteries, gyroscopic units, and circulating fans for temperature control. It was spin-stabilized for most of its flight, but its three-axis attitude control system was activated while taking photos. Luna 3 was radio-controlled from ground stations in the Soviet Union.

Mission

After launching on an 8K72 (number I1-8) rocket over the North Pole, the Blok-E escape stage was shut down by radio control to put Luna 3 on its course to the Moon. Initial radio contact showed that the signal from the space probe was only about one-half as strong as expected, and the internal temperature was rising. The spacecraft spin axis was reoriented and some equipment was shut down, resulting in a temperature drop from 40 celsius to about 30 celsius. At a distance of 60,000 to 70,000 km from the moon, the orientation system was turned on and the spacecraft rotation was stopped. The lower end of the craft was pointed at the sun, which was shining on the far side of the moon.

The space probe passed within 6,200 km of the moon near its south pole at the closest lunar approach at 14:16 UT on 6 October 1959, and continued on over the far side. On 7 October, the photocell on the upper end of the space probe detected the sunlit far side of the moon, and the photography sequence was started. The first picture was taken at 03:30 UT at a distance of 63,500 km from the moon, and the last picture was taken 40 minutes later from a distance of 66,700 km.

A total of 29 pictures were taken, covering 70% of the far side. After the photography was complete the spacecraft resumed spinning, passed over the north pole of the moon and returned towards the Earth. Attempts to transmit the pictures to the Soviet Union began on October 8 but the early attempts were unsuccessful due to the low signal strength. As Luna 3 drew closer to the Earth, a total of about 17 viewable but poor quality photographs were transmitted by 18 October. All contact with the probe was lost on 22 October 1959. The space probe was believed to have burned up in the Earth's atmosphere in March or April 1960. Another possibility was that it might have survived in orbit until 1962 or later.

Lunar photography

Luna-3 phototelegraph system at Tsiolkovsky State Museum of the History of Cosmonautics

1959 USSR stamp commemorating first photographs of the Far side of the Moon

The purpose of this experiment was to obtain photographs of the lunar surface as the spacecraft flew by the moon. The imaging system was designated Yenisey-2 and consisted of a dual-lens camera AFA-E1, an automatic film processing unit, and a scanner. The lenses on the camera were a 200 mm focal length, *f*/5.6 aperture objective and a 500 mm, *f*/9.5 objective. The camera carried 40 frames of temperature- and radiation-resistant 35 mm isochrome film. The 200 mm objective could image the full disk of the moon and the 500 mm could take an image of a region on the surface. The camera was fixed in the spacecraft and pointing was achieved by rotating the craft itself.

Luna-3 was the first successful three-axis stabilized spacecraft. During most of the mission, the spacecraft was spin stabilized, but for photography of the moon, the spacecraft oriented one axis toward the Sun and then a photocell was used to detect the moon and orient the cameras towards it. Detection of the moon signalled the camera cover to open and the photography sequence to start automatically. The images alternated between both cameras during the sequence. After photography was complete, the film was moved to an on-board processor where it was developed, fixed, and dried. Commands from the Earth were then given to move the film into a scanner where a spot produced by a cathode ray tube was projected through the film onto a photoelectric multiplier. The spot was scanned across the film and the photomultiplier converted the intensity of the light passing through the film into an electric signal which was transmitted to the Earth (via frequency-modulated analog video, similar to a facsimile). A frame could be scanned with a resolution of 1000 (horizontal) lines and the transmission could be done at a slow-scan television rate at large distances from the Earth and a faster rate at closer ranges.

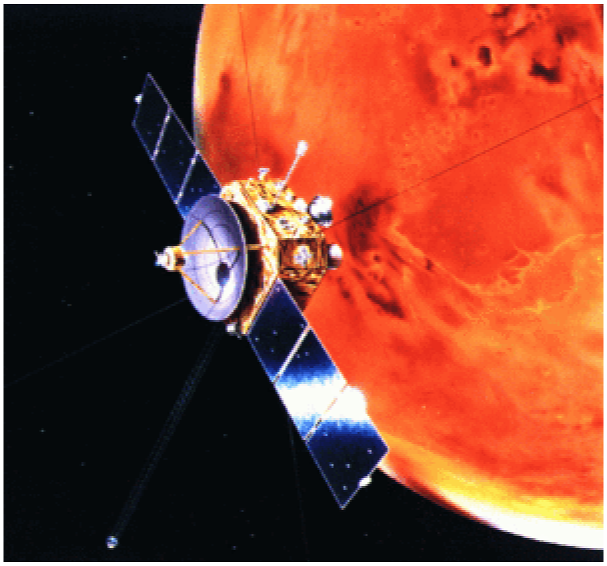
The camera took 29 pictures over 40 minutes on 7 October 1959, from 03:30 UT to 04:10 UT at distances ranging from 63,500 km to 66,700 km above the surface, covering 70% of the lunar far side. Seventeen (some say twelve) of these frames were successfully transmitted back to the Earth, and six were published (frames numbered 26, 28, 29, 31, 32, and 35). They were mankind's first views of the far hemisphere of the moon.

The imaging system was developed by P.F. Bratslavets and I.A. Rosselevich at the Leningrad Scientific Research Institute for Television and the returned images were processed and analyzed by Iu.N. Lipskii and his team at the Sternberg Astronomical Institute. The camera AFA-E1 was developed and manufactured by the KMZ factory (Krasnogorskiy Mekhanicheskiy Zavod).

Chapter- 6

Nozomi (Spacecraft)

Nozomi



Nozomi at Mars

Operator	JAXA
Mission type	Orbiter
Satellite of	Mars
Launch date	July 3, 1998, Uchinoura Space Center
Launch vehicle	M-V
Mission duration	December 9, 2003
COSPAR ID	1998-041A
Homepage	Nozomi official site

Mass	258 kilograms (570 lb)

Nozomi (のぞみ) (Japanese for "Wish" or "Hope," and known before launch as **Planet-B**) was planned as a Mars-orbiting aeronomy probe, but was unable to achieve Mars orbit due to electrical failures. Since 2003 it is in a roughly 2-year heliocentric orbit. Though its mission has been abandoned the spacecraft is still active.

It was constructed by the Institute of Space and Astronautical Science, University of Tokyo and launched on July 3, 1998 at 18:12:00 UTC with an on-orbit dry mass of 258 kg and 282 kg of propellant.

Nozomi was designed to study the upper Martian atmosphere and its interaction with the solar wind and to develop technologies for use in future planetary missions. Specifically, instruments on the spacecraft were to measure the structure, composition and dynamics of the ionosphere, aeronomy effects of the solar wind, the escape of atmospheric constituents, the intrinsic magnetic field, the penetration of the solar-wind magnetic field, the structure of the magnetosphere, and dust in the upper atmosphere and in orbit around Mars. The mission would have also returned images of Mars' surface.

Mission profile

Launch

After launch on the third M-V launch vehicle, Nozomi was put into an elliptical geocentric parking orbit with a perigee of 340 km and an apogee of 400,000 km.

Lunar swing-bys

The spacecraft used a lunar swingby on September 24, 1998 and another on December 18, 1998 to increase the apogee of its orbit.

Earth swing-by

It swung by Earth on December 20, 1998 at a perigee of about 1000 km. The gravitational assist from the swingby coupled with a 7 minute burn of the bipropellant rocket put Nozomi into an escape trajectory towards Mars. It was scheduled to arrive at Mars on October 11, 1999 at 7:45:14 UT, but a malfunctioning valve during the Earth swingby resulted in a loss of fuel and left the spacecraft with insufficient acceleration to reach its planned trajectory. Two course correction burns on December 21 used more propellant than planned, leaving the spacecraft short of fuel.

New mission plan

The new plan was for Nozomi to remain in heliocentric orbit for an additional four years, including two Earth flybys in December 2002 and June 2003, and encounter Mars at a slower relative velocity in December 2003.

First Earth flyby

On April 21, 2002 as Nozomi was approaching Earth for the gravity assist maneuver, powerful solar flares damaged the spacecraft's onboard communications and power systems. An electrical short occurred in a power cell used to control the attitude control heating system, allowing the hydrazine fuel to freeze. The fuel thawed out as the craft approached Earth and manoeuvres to put the craft on the correct trajectory for its Earth flyby were successful.

Second Earth flyby

Another Earth flyby within 11,000 km occurred on June 19, 2003. The fuel had completely thawed out for this maneuver because of the spacecraft's proximity to the Sun. However, on December 9, 2003, efforts to orient the craft to prepare it for a December 14, 2003 main thruster orbital insertion burn failed, and efforts to save the mission were abandoned. The small thrusters were fired on December 9, moving the closest approach distance to 1000 km so that the probe would not inadvertently impact on Mars and possibly contaminate the planet with Earth bacteria, since the orbiter had not been intended to land and was therefore not properly sterilized.

Mars flyby

The spacecraft flew by Mars on December 14, 2003 and went into a roughly 2-year heliocentric orbit. Though its mission has been abandoned the spacecraft is still active.

Intended Mars mission

Nozomi was to be inserted into a highly eccentric Mars orbit with a periareion 300 km above the surface, an apoareion of 15 Mars radii, and an inclination of 170 degrees with respect to the ecliptic plane. Shortly after insertion, the mast and antennas were to be deployed. The periareion would have been lowered to 150 km, the orbital period to about 38.5 hours. The spacecraft was to be spin stabilized at 7.5 rpm with its spin axis (and the dish antenna) pointed towards Earth. The periapsis portion of the orbit would have allowed in-situ measurements of the thermosphere and lower exosphere and remote sensing of the lower atmosphere and surface. The more distant parts of the orbit would be for study of the ions and neutral gas escaping from Mars and their interactions with the solar wind. The nominal mission was planned for one martian year (approximately two Earth years). An extended mission might have allowed operation of the mission for three to five years. The spacecraft was also to point its cameras at the martian moons Phobos and Deimos.

Spacecraft and subsystems

The Nozomi orbiter is a 0.58 meter high, 1.6 meter square prism with truncated corners. Extending out from two opposite sides are solar panel wings containing silicon solar cells which provide power to the spacecraft directly or via NiMH (nickel metal hydride) batteries. On the top surface is a dish antenna, and a propulsion unit protrudes from the bottom. A 5 m deployable mast and a 1 m boom extend from the sides, along with two pairs of thin wire antennas which measure 50 m tip to tip. Other instruments are also arranged along the sides of the spacecraft. Spacecraft communications are via X-band at 8410.93 MHz and S-band at 2293.89 MHz. The 14 instruments carried on Nozomi are an imaging camera, neutral mass spectrometer, dust counter, thermal plasma analyzer, magnetometer, electron and ion spectrum analyzers, ion mass spectrograph, high energy particles experiment, VUV imaging spectrometer, sounder and plasma wave detector, LF wave analyzer, electron temperature probe, and a UV scanner. The total mass budgeted for the science instruments was 33 kg. Radio science experiments were also possible using the existing radio equipment and an ultrastable oscillator. The total mass of Nozomi at launch including 282 kg of propellant was 540 kg.

Canada provided a $5 million thermal plasma analyser. This was the Canadian Space Agency's first participation in an interplanetary mission.

Chapter- 7

Galileo (Spacecraft)

***Galileo* Orbiter**

Galileo is prepared for mating with the IUS booster

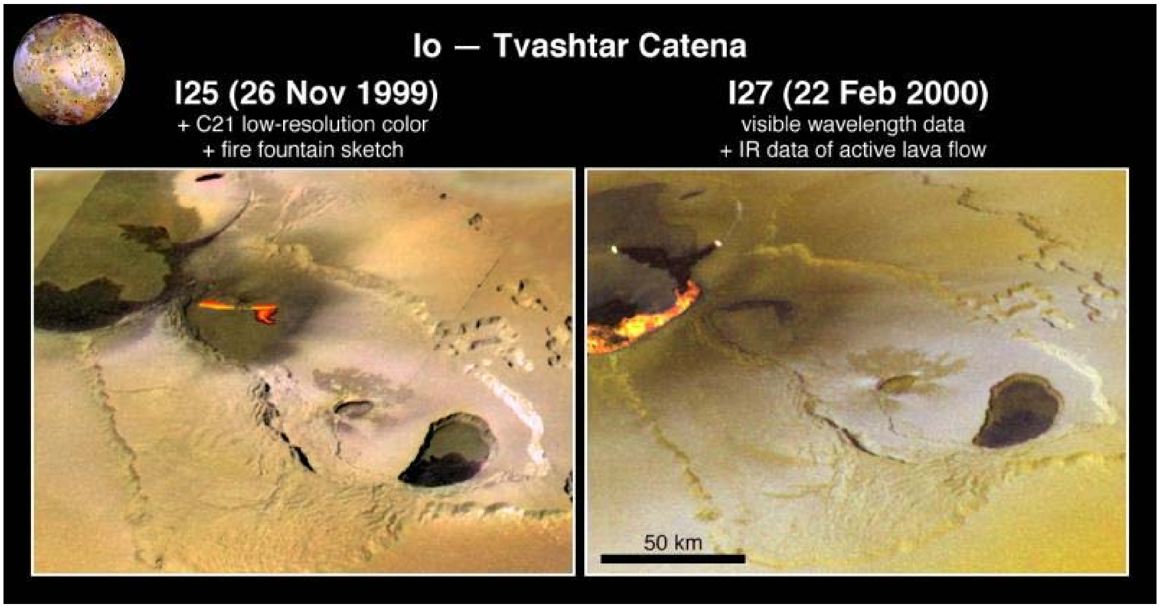
Operator	NASA
Mission type	Orbiter, Fly-by
Flyby of	Venus, Earth, 951 Gaspra, 243 Ida
Satellite of	**Jupiter**
Orbital insertion date	1995-12-08 01:20:00 UTC

Launch date	1989-10-18 16:53:00 UTC
Launch vehicle	Space Shuttle Atlantis Inertial Upper Stage
Launch site	KSC Launch Complex 39B Kennedy Space Center
Mission duration	December 8, 1995 - September 21, 2003 (deorbited 2003-09-21 18:57:00 UTC)
COSPAR ID	1989-084B
Homepage	*Galileo* Project Home Page
Mass	2,380 kg (5,200 lb)
Power	570 W (2 RTGs)

Galileo and Inertial Upper Stage being deployed after being launched by the Space Shuttle Atlantis on the STS-34 mission

Galileo and Inertial Upper Stage in space

The four largest moons of Jupiter photographed by *Galileo*



Galileo captures a dynamic eruption at Tvashtar Catena, a chain of volcanic bowls on Jupiter's moon Io

Galileo was an unmanned spacecraft sent by NASA to study the planet Jupiter and its moons. Named after the astronomer and Renaissance pioneer Galileo Galilei, it was launched on October 18, 1989 by the Space Shuttle *Atlantis* on the STS-34 mission. It arrived at Jupiter on December 7, 1995, a little more than six years later, via gravitational assist flybys of Venus and Earth.

Despite antenna problems, *Galileo* conducted the first asteroid flyby near 951 Gaspra, discovered the first asteroid moon Dactyl around asteroid 243 Ida, was the first spacecraft to orbit Jupiter, and launched the first probe into Jupiter's atmosphere .

The spacecraft measured atmospheric composition of Jupiter and directly observed ammonia clouds, which seems to be created from an outflow from lower depths. It also registered Io's volcanism and plasma interactions between the atmosphere with currents from Jupiter's atmosphere. Other studies gave support for the popular theory of liquid oceans under the icy surface of Europa. There was also indications of similar liquid-saltwater layers under the surfaces of Ganymede and Callisto, while Ganymede was shown to possess a magnetic field. New evidence was also found for existence of exospheres around Europa, Ganymede, and Callisto .

It was discovered that Jupiter's faint ring system is formed by dust from impacts on the four small inner moons. The extent and structure of Jupiter's magnetosphere was also mapped .

Galileo was the only direct observation point of comet Shoemaker-Levy 9's impact into the atmosphere of Jupiter.

On September 21, 2003, after 14 years in space and 8 years of service in the Jovian system, *Galileo's* mission was terminated by sending the orbiter into Jupiter's atmosphere at a speed of nearly 50 kilometres per second to avoid any chance of it contaminating local moons with bacteria from Earth. Of particular concern was the ice-crusted moon Europa, which, thanks to *Galileo*, scientists now suspect harbors a salt water ocean beneath its surface.

Mission overview

Galileo's launch had been significantly delayed by the hiatus in Space Shuttle launches that occurred after the *Challenger* space shuttle disaster. New safety protocols introduced as a result of the Challenger accident forced *Galileo* to use a lower-powered upper stage booster rocket, instead of a Centaur booster rocket, to send it from Earth orbit to Jupiter. Several gravitational slingshots, called a "VEEGA" or Venus Earth Earth Gravity Assist maneuver, provided the additional velocity required to reach its destination: Venus was flown by on February 10, 1990, and Earth twice, on December 8, 1990, and again on December 8, 1992. Along the way *Galileo* performed close observation of the asteroids 951 Gaspra (October 29, 1991) and 243 Ida (August 28, 1993), and discovered Ida's moon Dactyl. In 1994 *Galileo* was perfectly positioned to watch the fragments of comet Shoemaker-Levy 9 crash into Jupiter. Terrestrial telescopes had to wait to see the impact sites as they rotated into view.

Galileo's prime mission was a two-year study of the Jovian system. The spacecraft traveled around Jupiter in elongated ellipses, each orbit lasting about two months. The differing distances from Jupiter afforded by these orbits allowed *Galileo* to sample different parts of the planet's extensive magnetosphere. The orbits were designed for close up flybys of Jupiter's largest moons. Once *Galileo*'s prime mission was concluded, an extended mission followed starting on December 7, 1997; the spacecraft made a number of daring close flybys of Jupiter's moons Europa and Io. The closest approach was 180 km (112 mi) on October 15, 2001. The radiation environment near Io in particular was very unhealthy for *Galileo's* systems, and so these flybys were saved for the extended mission when loss of the spacecraft would be more acceptable.

Galileo's cameras were deactivated on January 17, 2002 after they had sustained irrecoverable radiation damage. NASA engineers were able to recover the damaged tape recorder electronics, and once more *Galileo* continued to return other scientific data until it was deorbited in 2003 as described above, performing one last scientific experiment — a measurement of Amalthea's mass as *Galileo* swung by.

The Galileo *spacecraft*

The Jet Propulsion Laboratory built the *Galileo* spacecraft and managed the *Galileo* mission for NASA. Germany supplied the propulsion module. NASA's Ames Research Center managed the probe, which was built by Hughes Aircraft Company.

At launch, the orbiter and probe together had a mass of 2,564 kilograms (5,653 pounds) and was seven metres tall. One section of the spacecraft rotated at 3 rpm, keeping *Galileo* stable and holding six instruments that gathered data from many different directions, including the fields and particles instruments. The other section of the spacecraft was an antenna, and data were periodically transmitted to it. Back on the ground the mission operations team used software containing 650,000 lines of programming code in the orbit sequence design process; 1,615,000 lines in the telemetry interpretation; and 550,000 lines of code in navigation.

Command and data handling

The CDH was actively redundant, with two parallel strings running at all times. It was composed of multiplexers (MUX), high-level modules (HLM), low-level modules (LLM), power converters (PC), bulk memory (BUM), data management subsystem bulk memory (DBUM), timing chains (TC), phase lock loops (PLL), Golay coders (GC), and hardware command decodes (HCD).

The spacecraft was controlled by six RCA 1802 Cosmac microprocessor CPUs: four on the spun side and two on the despun side. Each CPU was clocked at about 1.6 MHz, and fabricated on sapphire (Silicon on sapphire) which is a radiation-and static-hardened material ideal for spacecraft operation. This microprocessor was the first low-power CMOS processor chip, quite on a par with the 8-bit 6502 that was being built into the Apple II desktop computer at that time. *Galileo*'s attitude control system software was written in the HAL/S programming language, also used in the Space Shuttle program. Memory capacity provided by each BUM was 16K of RAM while the DBUMs each provided 8K of RAM. The BUMs and DBUMs provided storage for sequences and contain various buffers for telemetry data and interbus communication.

Every HLM and LLM was built up around a single 1802 microprocessor and 32K of RAM (for HLMs) or 16K of RAM (for LLMs). Two HLMs and two LLMs resided on the spun side while two LLMs were on the despun side.

Each HLM was responsible for the following functions: 1.) uplink command processing, 2.) maintenance of the spacecraft clock, 3.) movement of data over the data system bus, 4.) execution of stored sequences (time-event tables), 5.) telemetry control, and 6.) error recovery including system fault-protection monitoring and response.

Each LLM was responsible for the following functions: 1.) collect and format engineering data from the subsystems, 2.) provide the capability to issue coded and discrete commands to spacecraft users, 3.) recognize out-of-tolerance conditions on status inputs, and 4.) perform some system fault-protection functions.

Propulsion

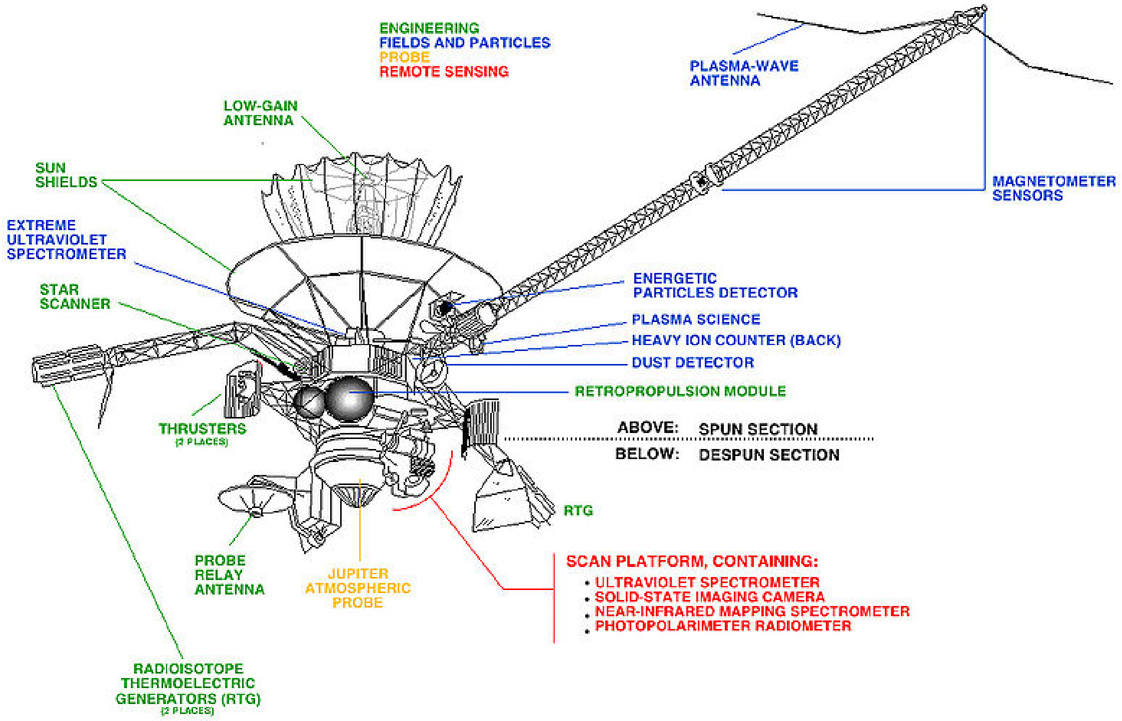
The Propulsion Subsystem consisted of a 400 N main engine and twelve 10 N thrusters together with propellant, storage and pressurizing tanks, and associated plumbing. The 10

N thrusters were mounted in groups of six on two 2-meter booms. The fuel for the system was 925 kg of monomethylhydrazine and nitrogen tetroxide. Two separate tanks held another 7 kg of helium pressurant. The Propulsion Subsystem was developed and built by Daimler Benz Aero Space AG (DASA) (formerly Messerschmitt–Bölkow–Blohm (MBB)) and provided by Germany, the major international partner in Project *Galileo*.

Electrical power

Solar panels were not a practical solution for *Galileo'*s power needs at Jupiter's distance from the Sun (it would have needed a *minimum* of 65 square metres (700 ft²) of solar panels); as for batteries, they would have been prohibitively massive. The solution adopted consisted of two radioisotope thermoelectric generators (RTGs). The RTGs powered the spacecraft through the radioactive decay of plutonium-238. The heat emitted by this decay was converted into electricity for the spacecraft through the solid-state Seebeck effect. This provided a reliable and long-lasting source of electricity unaffected by the cold space environment and high radiation fields such as those encountered in Jupiter's magnetosphere.

Each GPHS-RTG, mounted on a 5-meter long boom, carried 7.8 kilograms (17.2 lb) of ^{238}Pu. Each RTG contained 18 separate heat source modules, and each module encased four pellets of plutonium dioxide, a ceramic material resistant to fracturing. The modules were designed to survive a range of hypothetical accidents: launch vehicle explosion or fire, re-entry into the atmosphere followed by land or water impact, and post-impact situations. An outer covering of graphite provided protection against the structural, thermal, and eroding environments of a potential re-entry. Additional graphite components provided impact protection, while iridium cladding of the fuel cells provided post-impact containment. The RTGs produced about 570 watts at launch. The power output initially decreased at the rate of 0.6 watts per month and was 493 watts when *Galileo* arrived at Jupiter.



Overview of *Galileo*'s components

As the launch of *Galileo* neared, anti-nuclear groups, concerned over what they perceived as an unacceptable risk to the public's safety from *Galileo*s RTGs, sought a court injunction prohibiting *Galileo*s launch. RTGs had been used for years in planetary exploration without mishap: the Lincoln Experimental Satellites 8/9, launched by the U.S. Department of Defense, had 7% more plutonium on board than *Galileo*, and the two Voyager spacecraft each carried 80% as much plutonium as *Galileo* did. However, activists remembered the messy crash of the Soviet Union's nuclear-powered Cosmos 954 satellite in Canada in 1978, and the 1986 Challenger accident had raised public awareness of the possibility of explosive spacecraft failures. Also, no RTGs had ever been made to swing past the Earth at close range and high speed, as *Galileo*s Venus-Earth-Earth Gravity Assist trajectory required it to do. This created a novel mission failure modality that might plausibly have entailed total dispersal of *Galileo*s plutonium in the Earth's atmosphere. Scientist Carl Sagan, for example, a strong supporter of the *Galileo* mission, said in 1989 that "there is nothing absurd about either side of this argument."

After the Challenger accident, a study considered additional shielding and eventually rejected it, in part because such a design significantly increased the overall risk of mission failure and only shifted the other risks around (for example, if a failure on orbit had occurred, additional shielding would have significantly increased the consequences of a ground impact).

Instrumentation overview

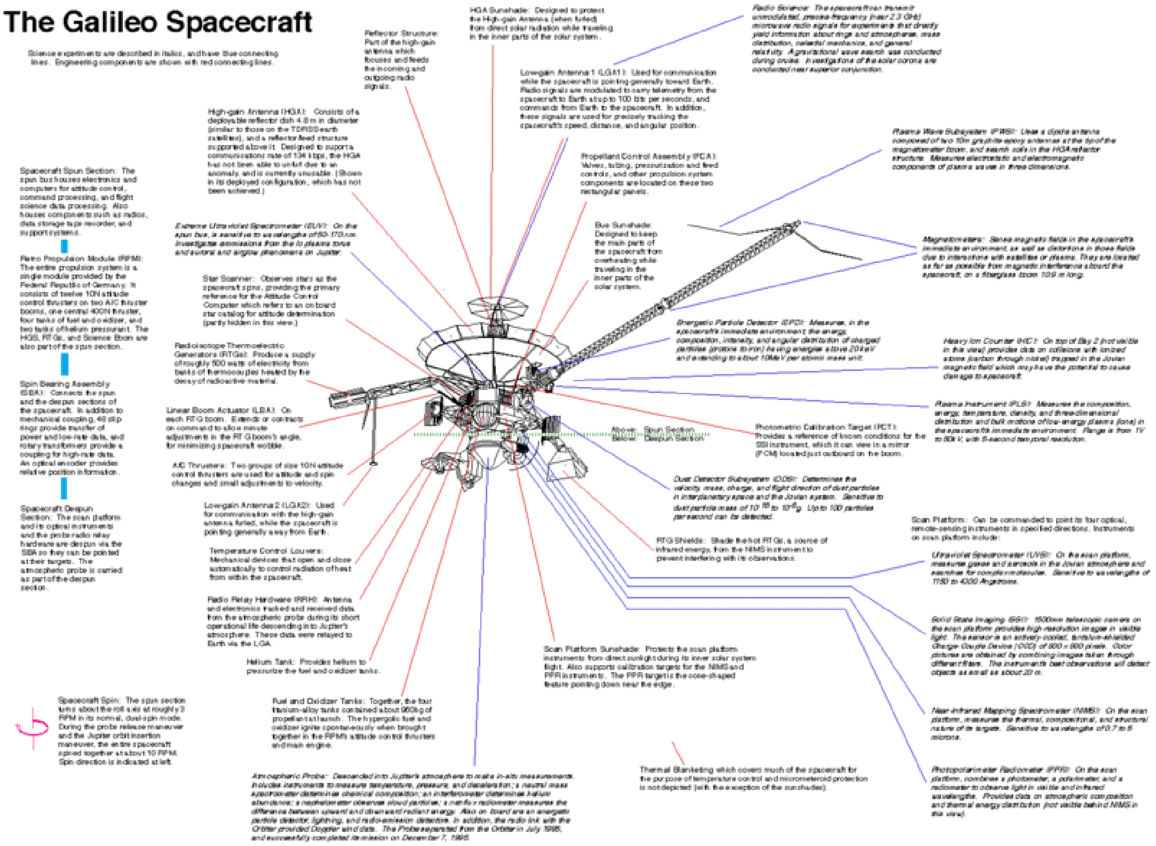
Scientific instruments to measure fields and particles were mounted on the spinning section of the spacecraft, together with the main antenna, power supply, the propulsion module and most of the *Galileo* computers and control electronics. The sixteen instruments, weighing 118 kg altogether, included magnetometer sensors mounted on an 11 m boom to minimize interference from the spacecraft; a plasma instrument for detecting low energy charged particles and a plasma wave detector to study waves generated by the particles; a high energy particle detector; and a detector of cosmic and Jovian dust. It also carried the Heavy Ion Counter, an engineering experiment added to assess the potentially hazardous charged particle environments the spacecraft flew through, and an added Extreme Ultraviolet detector associated with the UV spectrometer on the scan platform.

The despun section's instruments included the camera system; the near infrared mapping spectrometer to make multi-spectral images for atmospheric and moon surface chemical analysis; ultraviolet spectrometer to study gases; and photo-polarimeter radiometer to measure radiant and reflected energy. The camera system was designed to obtain images of Jupiter's satellites at resolutions from 20 to 1,000 times better than *Voyager*'s best, because *Galileo* flew closer to the planet and its inner moons and because the CCD sensor in *Galileo'*s camera was more sensitive and had a broader color detection band than the vidicons of *Voyager*.

Instrumentation details

The following information was taken directly from NASA's *Galileo* legacy site.

Despun section


The Galileo Spacecraft

Science experiments are described in italics, and have blue connecting lines. Engineering components are shown with red connecting lines.

Spacecraft Spun Section: The spun bus houses electronics and computers for attitude control, command processing, and flight science data processing. Also houses components such as radios, data storage tape recorder, and support systems.

Retro Propulsion Module (RPM): The entire propulsion system is a single module provided by the Federal Republic of Germany. It consists of twelve 10N attitude control thrusters on two A/C thruster booms, one central 400N thruster, four tanks of fuel and oxidizer, and two tanks of helium pressurant. The HGS, RTGs, and Science Boom are also part of the spun section.

Spin Bearing Assembly (SBA): Connects the spun and the despun sections of the spacecraft. In addition to mechanical coupling, 48 slip rings provide transfer of power and low-rate data, and rotary transformers provide a coupling for high-rate data. An optical encoder provides relative position information.

Spacecraft Despun Section: The scan platform and its optical instruments and the probe radio relay hardware are despun via the SBA so they can be pointed at their targets. The atmospheric probe is carried as part of the despun section.

Spacecraft Spin: The spun section turns about the roll axis at roughly 3 RPM in its normal, dual-spin mode. During the probe release maneuver and the Jupiter orbit insertion maneuver, the entire spacecraft spined together at about 10 RPM. Spin direction is indicated at left.

Reflector Structure: Part of the high-gain antenna which focuses and feeds the incoming and outgoing radio signals.

High-gain Antenna (HGA): Consists of a deployable reflector dish 4.8 m in diameter (similar to those on the TDRSS earth satellites), and a reflector feed structure supported above it. Designed to support a communications rate of 134 kbps, the HGA has not been able to unfurl due to an anomaly, and is currently unusable. (Shown in its deployed configuration, which has not been achieved.)

Extreme Ultraviolet Spectrometer (EUV): On the spun bus, is sensitive to wavelengths of 50-170 nm. Investigates emissions from the Io plasma torus and auroral and airglow phenomena on Jupiter.

Star Scanner: Observes stars as the spacecraft spins, providing the primary reference for the Attitude Control Computer which refers to an on board star catalog for attitude determination (partly hidden in this view.)

Radioisotope Thermoelectric Generators (RTGs): Produce a supply of roughly 500 watts of electricity from banks of thermocouples heated by the decay of radioactive material.

Linear Boom Actuator (LBA): On each RTG boom. Extends or contracts on command to allow minute adjustments in the RTG boom's angle, for minimizing spacecraft wobble.

A/C Thrusters: Two groups of size 10N attitude control thrusters are used for attitude and spin changes and small adjustments to velocity.

Low-gain Antenna 2 (LGA2): Used for communication with the high-gain antenna furled, while the spacecraft is pointing generally away from Earth.

Temperature Control Louvers: Mechanical devices that open and close automatically to control radiation of heat from within the spacecraft.

Radio Relay Hardware (RRH): Antenna and electronics tracked and received data from the atmospheric probe during its short operational life descending into Jupiter's atmosphere. These data were relayed to Earth via the LGA.

Helium Tank: Provides helium to pressurize the fuel and oxidizer tanks.

Fuel and Oxidizer Tanks: Together, the four titanium-alloy tanks contained about 960kg of propellant at launch. The hypergolic fuel and oxidizer ignite spontaneously when brought together in the RPM's attitude control thrusters and main engine.

Atmospheric Probe: Descended into Jupiter's atmosphere to make in-situ measurements. Includes instruments to measure temperature, pressure, and deceleration; a neutral mass spectrometer determines chemical composition; an interferometer determines helium abundance; a nephelometer observes cloud particles; a net flux radiometer measures the difference between upward and downward radiant energy. Also on board are an energetic particle detector, lightning, and radio-emission detectors. In addition, the radio link with the Orbiter provided Doppler wind data. The Probe separated from the Orbiter in July 1995, and successfully completed its mission on December 7, 1995.

HGA Sunshade: Designed to protect the High-gain Antenna (when furled) from direct solar radiation while traveling in the inner parts of the solar system.

Low-gain Antenna 1 (LGA1): Used for communication while the spacecraft is pointing generally toward Earth. Radio signals are modulated to carry telemetry from the spacecraft to Earth at up to 100 bits per seconds, and commands from Earth to the spacecraft. In addition, these signals are used for precisely tracking the spacecraft's speed, distance, and angular position.

Radio Science: The spacecraft can transmit unmodulated, precise-frequency (near 2.3 GHz) microwave radio signals for experiments that directly yield information about rings and atmospheres, mass distribution, celestial mechanics, and general relativity. A gravitational wave search was conducted during cruise. Investigations of the solar corona are conducted near superior conjunction.

Propellant Control Assembly (PCA): Valves, tubing, pressurization and feed controls, and other propulsion system components are located on these two rectangular panels.

Bus Sunshade: Designed to keep the main parts of the spacecraft from overheating while traveling in the inner parts of the solar system.

Plasma Wave Subsystem (PWS): Uses a dipole antenna composed of two 10m graphite-epoxy antennas at the top of the magnetometer boom, and search coils in the HGA reflector structure. Measures electrostatic and electromagnetic components of plasma waves in three dimensions.

Magnetometers: Sense magnetic fields in the spacecraft's immediate environment, as well as distortions in those fields due to interactions with satellites or plasma. They are located as far as possible from magnetic interference aboard the spacecraft, on a fiberglass boom 10.9 m long.

Energetic Particle Detector (EPD): Measures, in the spacecraft's immediate environment, the energy, composition, intensity, and angular distribution of charged particles (protons to iron) having energies above 20 keV and extending to about 10MeV per atomic mass unit.

Heavy Ion Counter (HIC): On top of Bay 2 (not visible in this view) provides data on collisions with ionized atoms (carbon through nickel) trapped in the Jovian magnetic field which may have the potential to cause damage to spacecraft.

Plasma Instrument (PLS): Measures the composition, energy, temperature, density, and three-dimensional distribution and bulk motions of low-energy plasma (ions) in the spacecraft's immediate environment. Range is from 1V to 50kV, with 5-second temporal resolution.

Above: Spun Section
Below: Despun Section

Photometric Calibration Target (PCT): Provides a reference of known conditions for the SSI instrument, which it can view in a mirror (PCM) located just outboard on the boom.

Dust Detector Subsystem (DDS): Determines the velocity, mass, charge, and flight direction of dust particles in interplanetary space and the Jovian system. Sensitive to dust particle mass of 10^{-16} to 10^{-6}g. Up to 100 particles per second can be detected.

RTG Shields: Shade the hot RTGs, a source of infrared energy, from the NIMS instrument to prevent interfering with its observations.

Scan Platform: Can be commanded to point its four optical, remote-sensing instruments in specified directions. Instruments on scan platform include:

Ultraviolet Spectrometer (UVS): On the scan platform, measures gases and aerosols in the Jovian atmosphere and searches for complex molecules. Sensitive to wavelengths of 1150 to 4300 Angstroms.

Solid State Imaging (SSI): 1500mm telescopic camera on the scan platform provides high-resolution images in visible light. The sensor is an actively-cooled, tantalum-shielded Charge-Couple Device (CCD) of 800 x 800 pixels. Color pictures are obtained by combining images taken through different filters. The instrument's best observations will detect objects as small as about 20 m.

Near-infrared Mapping Spectrometer (NIMS): On the scan platform, measures the thermal, compositional, and structural nature of its targets. Sensitive to wavelengths of 0.7 to 5 microns.

Photopolarimeter Radiometer (PPR): On the scan platform, combines a photometer, a polarimeter, and a radiometer to observe light in visible and infrared wavelengths. Provides data on atmospheric composition and thermal energy distribution (not visible behind NIMS in this view).

Scan Platform Sunshade: Protects the scan platform instruments from direct sunlight during its inner solar system flight. Also supports calibration targets for the NIMS and PPR instruments. The PPR target is the cone-shaped feature pointing down near the edge.

Thermal Blanketing which covers much of the spacecraft for the purpose of temperature control and micrometeroid protection is not depicted (with the exception of the sunshades).

Highly detailed diagram of *Galileo* instruments and subsystems.

Solid-State Imaging camera of the Galileo spacecraft

Solid State Imager (SSI)

The SSI is an 800 by 800 pixel solid state camera consisting of an array of silicon sensors called a "charge coupled device" (CCD). Galileo was one of the first spacecraft to be equipped with CCD camera. The optical portion of the camera is built as a Cassegrain telescope. Light is collected by the primary mirror and directed to a smaller secondary mirror that channels it through a hole in the center of the primary mirror and onto the CCD. The CCD sensor is shielded from radiation, a particular problem within the harsh Jovian magnetosphere. The shielding is accomplished by means of a 10 mm thick layer of tantalum surrounding the CCD except where the light enters the system. An eight position filter wheel is used to obtain images at specific wavelengths. The images are then combined electronically on Earth to produce color images. The spectral response of the SSI ranges from about 0.4 to 1.1 micrometres. The SSI weighs 29.7 kilograms and consumes, on average, 15 watts of power.

Near-Infrared Mapping Spectrometer (NIMS)

The NIMS instrument is sensitive from 0.7 to 5.2 micrometre wavelength IR light, overlapping the wavelength range of SSI. The telescope associated with NIMS is all reflective (uses mirrors and no lenses) with an aperture of 229 mm. The spectrometer of NIMS uses a grating to disperse the light collected by the telescope. The dispersed spectrum of light is focused on detectors of indium antimonide and silicon. The NIMS weighs 18 kilograms and uses 12 watts of power on average.

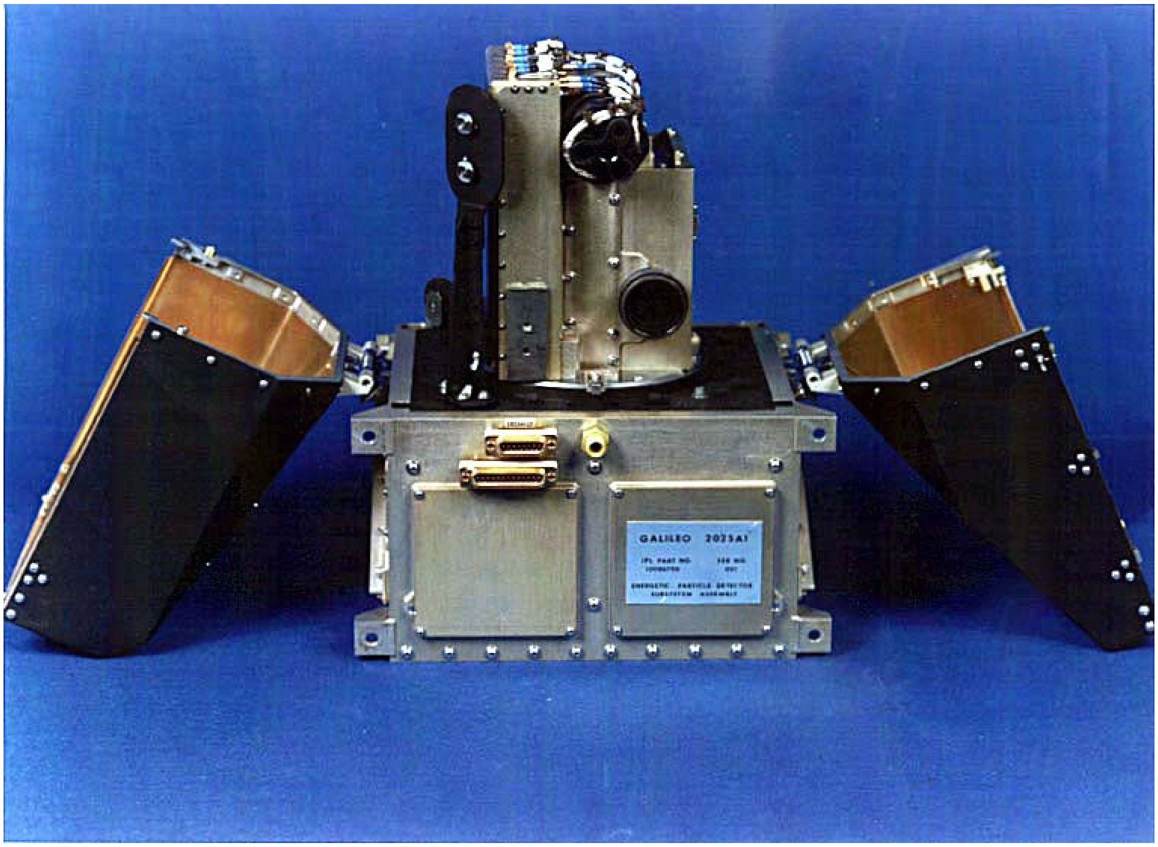
Ultraviolet Spectrometer / Extreme Ultraviolet Spectrometer (UVS/EUV)

The Cassegrain telescope of the UVS has a 250 mm aperture and collects light from the observation target. Both the UVS and EUV instruments use a ruled grating to disperse this light for spectral analysis. This light then passes through an exit slit into photomultiplier tubes that produce pulses or "sprays" of electrons. These electron pulses are counted, and these count numbers are the data that are sent to Earth. The UVS is mounted on the scan platform and can be pointed to an object in inertial space. The EUV is mounted on the spun section of the spacecraft. As *Galileo* spins, the EUV observes a narrow ribbon of space perpendicular to the spin axis. The two instruments combined weigh about 9.7 kilograms and use 5.9 watts of power.

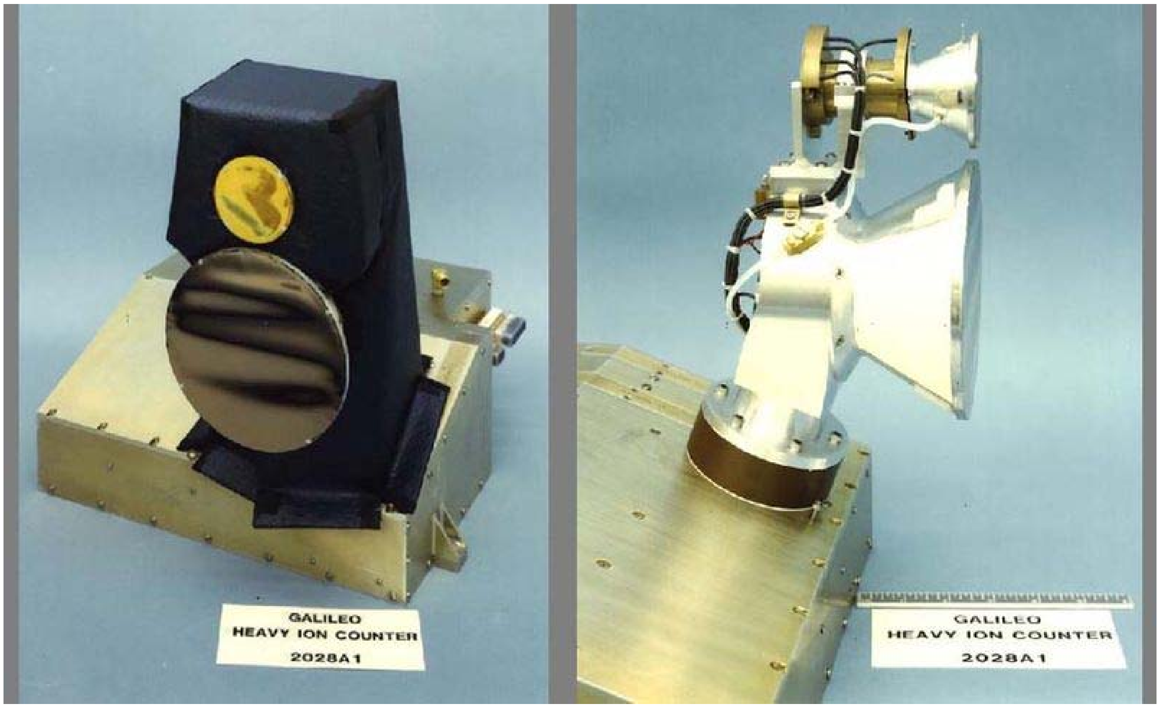
Photopolarimeter-Radiometer (PPR)

The PPR has seven radiometry bands. One of these uses no filters and observes all the radiation, both solar and thermal. Another band lets only solar radiation through. The difference between the solar- plus-thermal and the solar-only channels gives the total thermal radiation emitted. The PPR also measured in five broadband channels that span the spectral range from 17 to 110 micrometres. The radiometer provides data on the temperatures of the Jovian satellites and Jupiter's atmosphere. The design of the instrument is based on that of an instrument flown on the Pioneer Venus spacecraft. A 100 mm aperture reflecting telescope collects light, directs it to a series of filters, and, from there, measurements are performed by the detectors of the PPR. The PPR weighs 5.0 kilograms and consumes about 5 watts of power.

Spun section



Energetic Particles Detector of the Galileo spacecraft



Heavy Ion Counter of the Galileo spacecraft

Dust Detector Subsystem (DDS)

The Dust Detector Subsystem (DDS) was used to measure the mass, electric charge, and velocity of incoming particles. The masses of dust particles that the DDS can detect go from 10^{-16} to 10^{-7} grams. The speed of these small particles can be measured over the range of 1 to 70 kilometers per second. The instrument can measure impact rates from 1 particle per 115 days (10 megaseconds) to 100 particles per second. These particles will help determine dust origin and dynamics within the magnetosphere. The DDS weighs 4.2 kilograms and uses an average of 5.4 watts of power.

Energetic Particles Detector (EPD)

The energetic particles detector (EPD) is designed to measure the numbers and energies of ions and electrons whose energies exceed about 20 keV (3.2 fJ). The EPD can also measure the direction of travel of such particles and, in the case of ions, can determine their composition (whether the ion is oxygen or sulfur, for example). The EPD uses silicon solid state detectors and a time-of-flight detector system to measure changes in the energetic particle population at Jupiter as a function of position and time. These measurements will tell us how the particles get their energy and how they are transported through Jupiter's magnetosphere. The EPD weighs 10.5 kilograms and uses 10.1 watts of power on average.

Heavy Ion Counter (HIC)

The HIC is really a repackaged and updated version of some parts of the flight spare of the Voyager Cosmic Ray System. The HIC detects heavy ions using stacks of single crystal silicon wafers. The HIC can measure heavy ions with energies as low as 6 MeV (1 pJ) and as high as 200 MeV (32 pJ) per nucleon. This range includes all atomic substances between carbon and nickel. The HIC and the EUV share a communications link and, therefore, must share observing time. The HIC weighs 8 kilograms and uses an average of 2.8 watts of power.

Magnetometer (MAG)

The magnetometer (MAG) uses two sets of three sensors. The three sensors allow the three orthogonal components of the magnetic field section to be measured. One set is located at the end of the magnetometer boom and, in this position, is about 11 m from the spin axis of the spacecraft. The second set, designed to detect stronger fields, is 6.7 m from the spin axis. The boom is used to remove the MAG from the immediate vicinity of the spacecraft to minimize magnetic effects from the spacecraft. However, not all these effects can be eliminated by distancing the instrument. The rotation of the spacecraft is used to separate natural magnetic fields from engineering induced fields. Another source of potential error in measurement comes from bending and twisting of the long magnetometer boom. To account for these motions, a calibration coil is mounted rigidly on the spacecraft and puts out a reference magnetic field during calibrations. The magnetic field at the surface of the Earth has a strength of about 50,000 nT. At Jupiter, the outboard (11 m) set of sensors can measure magnetic field strengths in the range from ±32 to ±512 nT while the inboard (6.7 m) set is active in the range from ±512 to ±16,384 nT. The MAG experiment weighs 7 kilograms and uses 3.9 watts of power.

Plasma Subsystem (PLS)

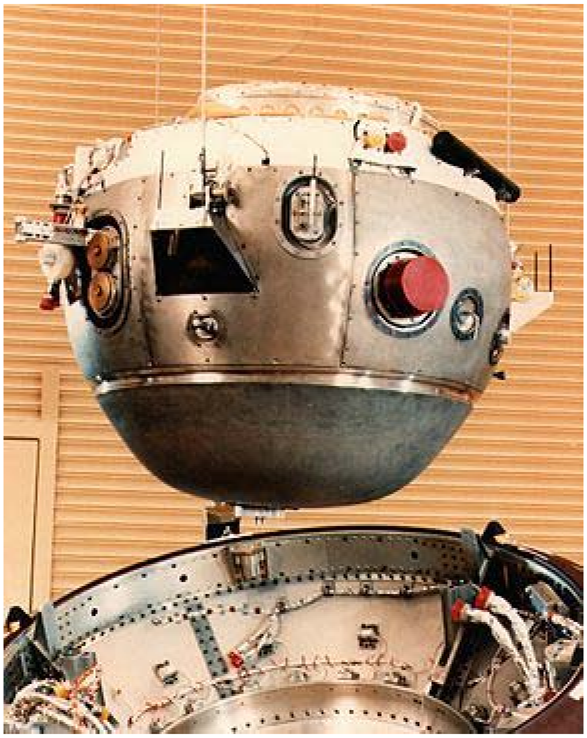
The PLS uses seven fields of view to collect charged particles for energy and mass analysis. These fields of view cover most angles from 0 to 180 degrees, fanning out from the spin axis. The rotation of the spacecraft carries each field of view through a full circle. The PLS will measure particles in the energy range from 0.9 eV to 52 keV (0.1 aJ to 8.3 fJ). The PLS weighs 13.2 kilograms and uses an average of 10.7 watts of power.

Plasma Wave Subsystem (PWS)

An electric dipole antenna is used to study the electric fields of plasmas, while two search coil magnetic antennas studied the magnetic fields. The electric dipole antenna is mounted at the tip of the magnetometer boom. The search coil magnetic antennas are mounted on the high-gain antenna feed. Nearly simultaneous measurements of the electric and magnetic field spectrum allowed electrostatic waves to be distinguished from electromagnetic waves. The PWS weighs 7.1 kilograms and uses an average of 9.8 watts.

Galileo'*s atmospheric entry probe*

Galileo Probe

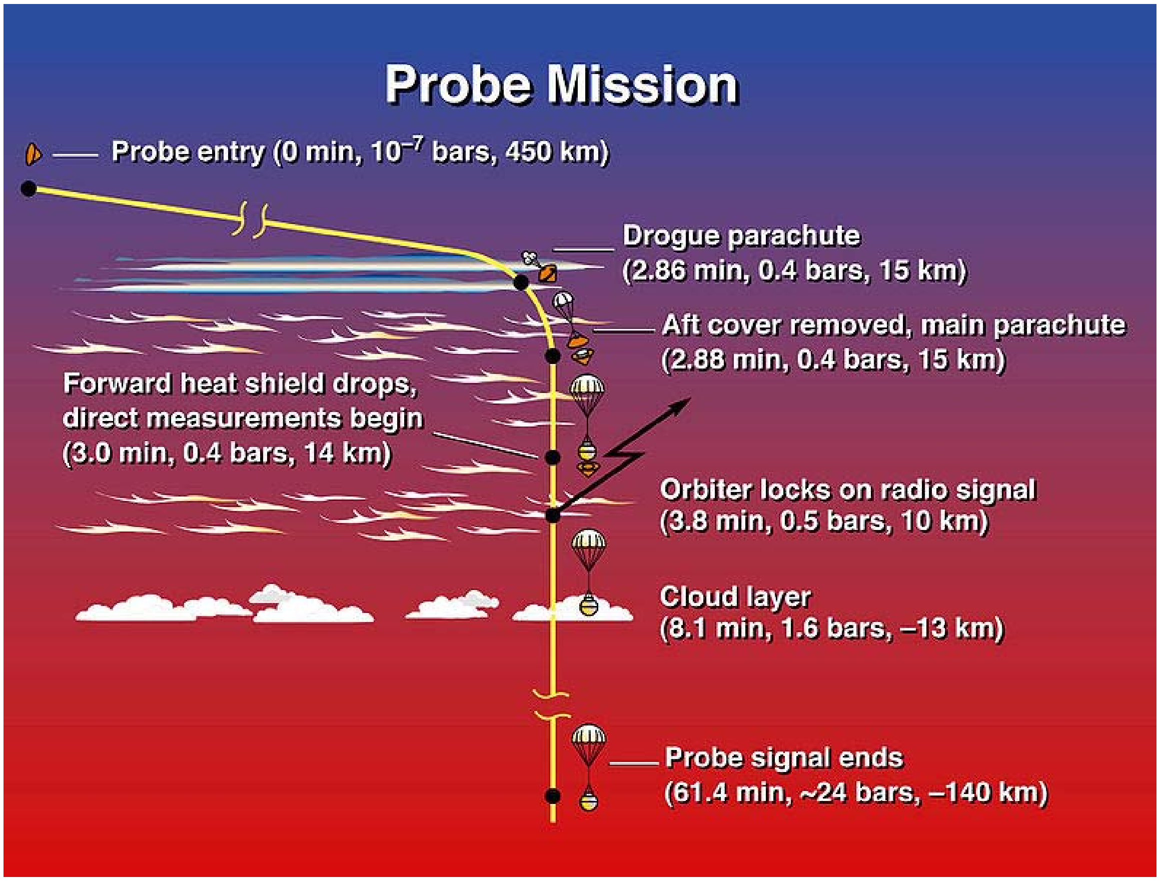


The *Galileo* Probe Descent Module

Operator	NASA
Mission type	Atmospheric probe
Launch date	July 13, 1995
Launch vehicle	Space Shuttle Atlantis Inertial Upper Stage Galileo Orbiter
Launch site	KSC Launch Complex 39B Kennedy Space Center
Mission duration	December 7, 1995 (57.6 minutes)
COSPAR ID	1989-084E
Homepage	*Galileo* Project Home Page
Mass	339 kg (750 lb)
Power	580 W ($LiSO_2$ battery)

Orbital elements

Eccentricity	1.03116
Inclination	8.151°
Periapsis	0.9928 RJ



Timeline of probe atmospheric entry.

The 339 kilogram atmospheric probe, built by Hughes Aircraft Company at its El Segundo, California plant, measured about 1.3 meters across. Inside the heat shield, the scientific instruments were protected from ferocious heat during entry. The probe had to withstand extreme heat and pressure on its high speed journey at 47.8 km/s.

The probe was released from the main spacecraft in July 1995, five months before reaching Jupiter, and entered Jupiter's atmosphere with no braking beforehand. It was slowed from the probe's arrival speed of about 47 kilometers per second to subsonic speed in less than two minutes.

This was by far the most difficult atmospheric entry ever attempted; the probe had to withstand 230 g and the probe's 152 kg heat shield made up almost half of the probe's total mass, and lost 80 kg during the entry. NASA built a special laboratory, the Giant

Planet Facility to simulate the heat load, which was similar to that of an ICBM-style straight-down reentry through a thermonuclear fireball. It then deployed its 2.5-meter (8 ft) parachute, and dropped its heat shield.

As the probe descended through 150 kilometers of the top layers of the atmosphere, it collected 58 minutes of data on the local weather. It only stopped transmitting when ambient pressure exceeded 23 atmospheres and temperature reached 153 °C (307 °F). The data was sent to the spacecraft overhead, then transmitted back to Earth. Each of 2 L-band transmitters operated at 128 bits per second and sent nearly identical streams of scientific data to the orbiter. All the probe's electronics were powered by lithium sulfur dioxide ($LiSO_2$) batteries that provided a nominal power output of about 580 watts with an estimated capacity of about 21 ampere-hours on arrival at Jupiter.

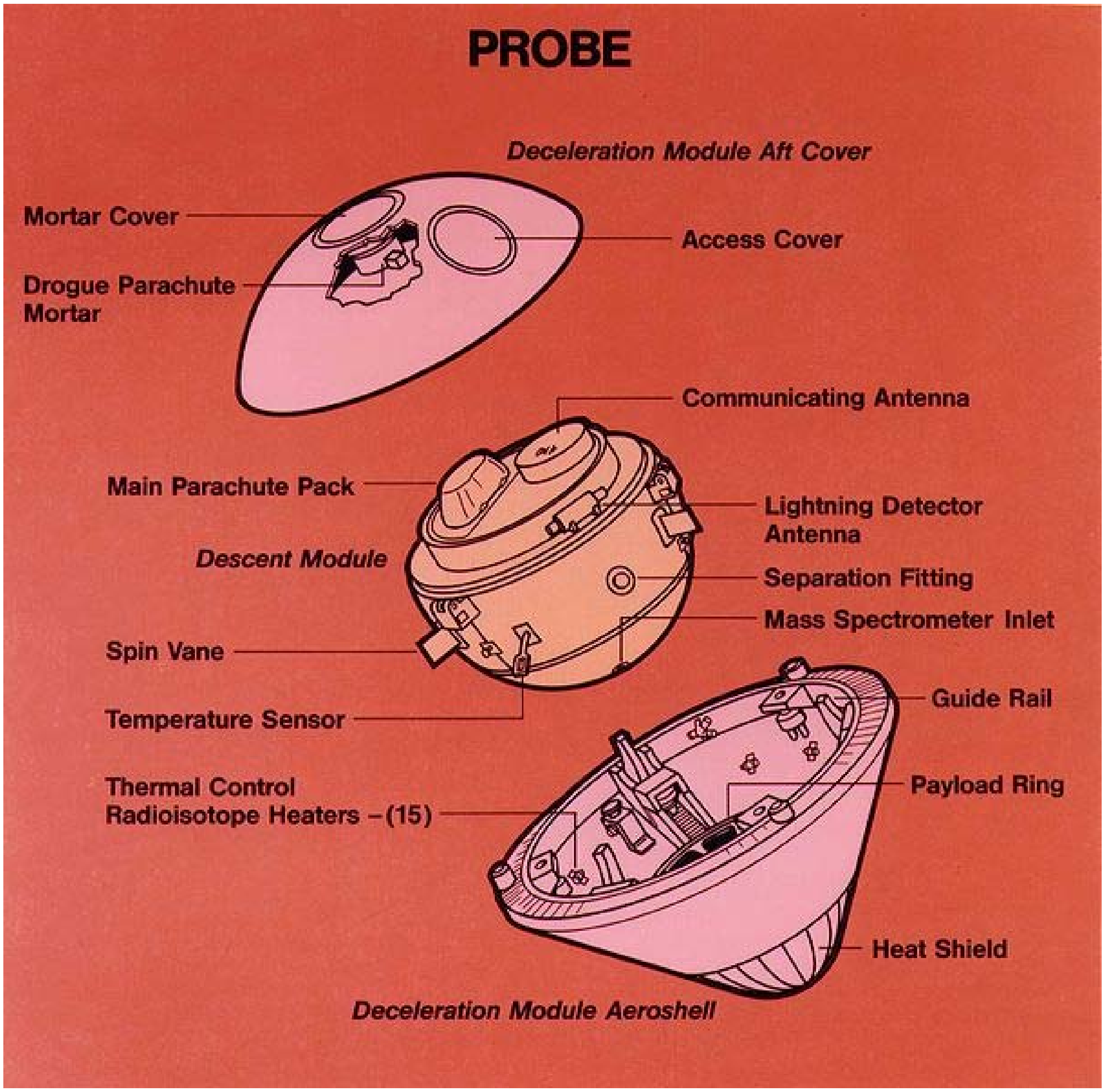


Diagram of *Galileo* atmospheric entry probe instruments and subsystems.

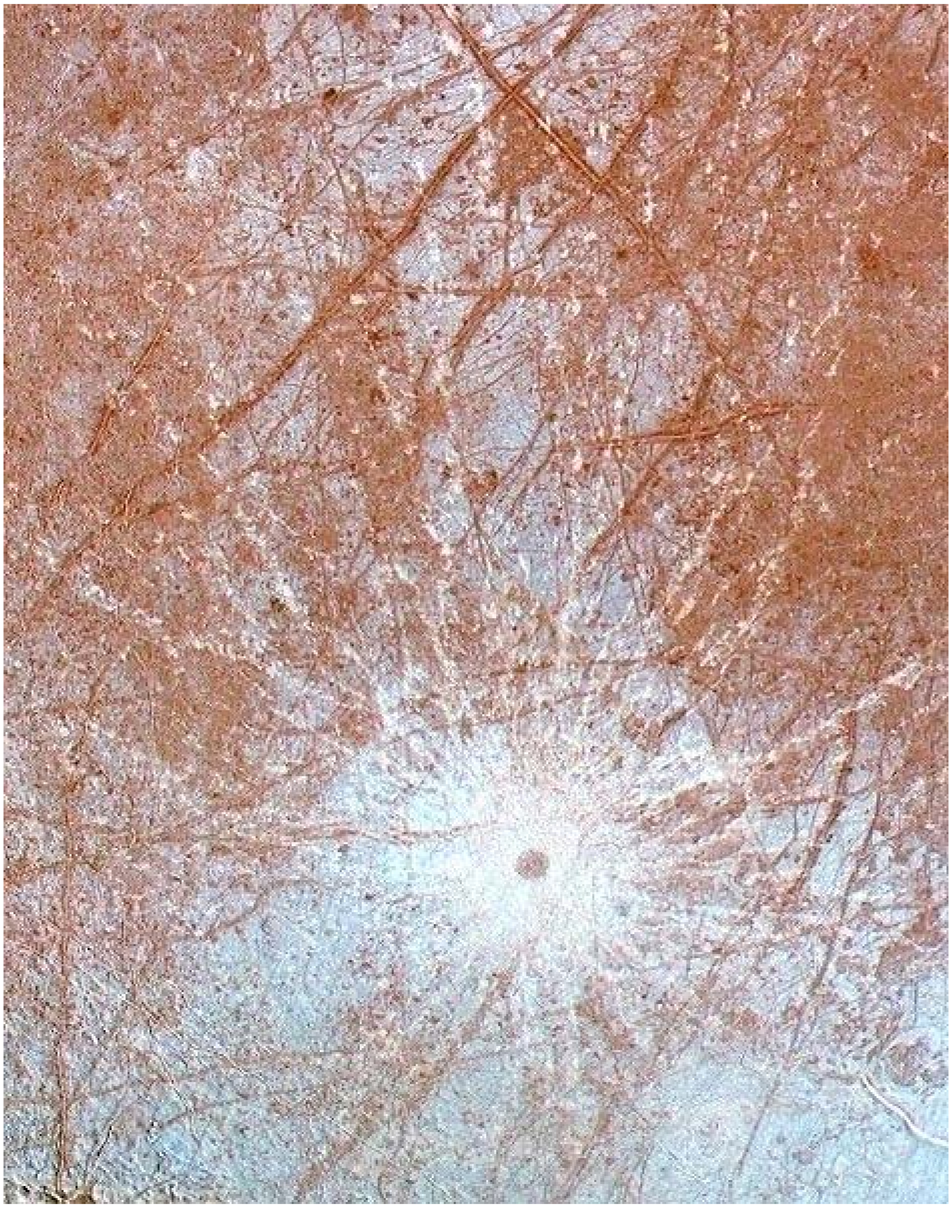
The probe included six instruments for taking data on its plunge into Jupiter:

- an *atmospheric structure instrument group* measuring temperature, pressure and deceleration,
- a *neutral mass spectrometer* and
- a *helium-abundance interferometer* supporting atmospheric composition studies,
- a *nephelometer* for cloud location and cloud-particle observations,
- a *net-flux radiometer* measuring the difference between upward and downward radiant flux at each altitude, and
- a *lightning/radio-emission instrument* with an energetic-particle detector that measured light and radio emissions associated with lightning and energetic particles in Jupiter's radiation belts.

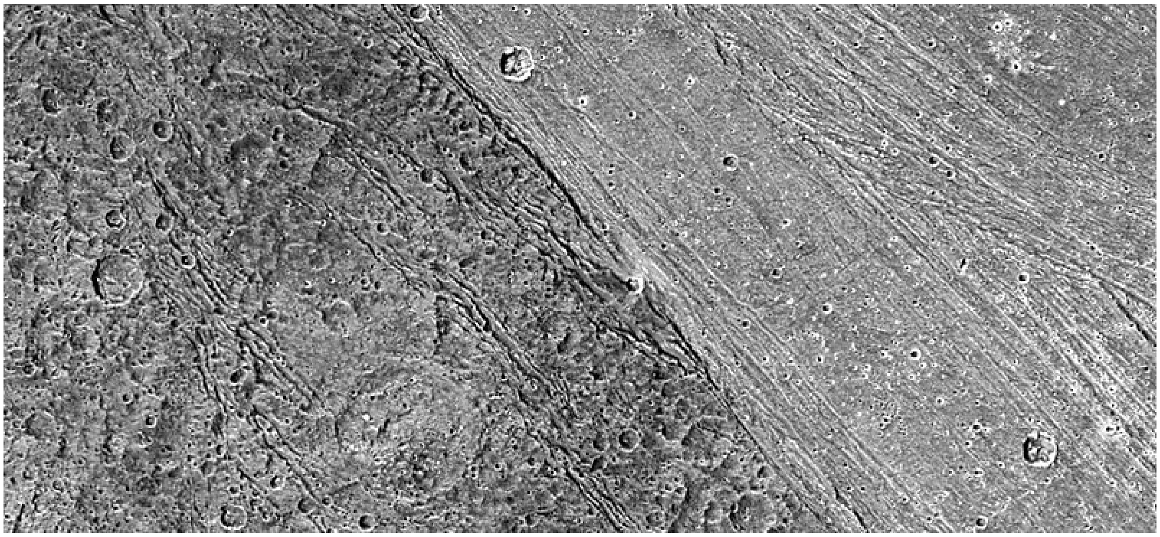
Total data returned from the probe was about 3.5 megabits (~458752 bytes). The probe stopped transmitting before the line of sight link with the orbiter was cut. The likely proximal cause of the final probe failure was overheating, which sensors indicated before signal loss.

The atmosphere through which the probe descended was somewhat more turbulent and hotter than expected. The probe was eventually completely destroyed as it continued to descend. The parachute would have melted first, roughly 30 minutes later, then the aluminum components after another 40 minutes of free fall. The titanium structure would have lasted 6.5 hours more before disintegrating. Due to the high pressure, the droplets of metals from the probe would finally have vaporised once their critical temperature had been reached, and mixed with Jupiter's liquid metallic hydrogen interior.

Science performed by the Galileo *Orbiter at Jupiter*



Pwyll crater on Europa



Terrain on Ganymede

After arriving on December 7, 1995 and completing 35 orbits around Jupiter throughout a nearly eight year mission, the *Galileo* Orbiter was destroyed during a controlled impact with Jupiter on September 21, 2003. During that intervening time, *Galileo* forever changed the way scientists saw Jupiter and provided a wealth of information on the moons orbiting the planet which will be studied for years to come. Culled from NASA's press kit, the top orbiter science results were:

- *Galileo* made the first observation of ammonia clouds in another planet's atmosphere. The atmosphere creates ammonia ice particles from material coming up from lower depths.
- The moon Io was confirmed to have extensive volcanic activity that is 100 times greater than that found on Earth. The heat and frequency of eruptions are reminiscent of early Earth.
- Complex plasma interactions in Io's atmosphere create immense electrical currents which couple to Jupiter's atmosphere.
- Several lines of evidence from *Galileo* support the theory that liquid oceans exist under Europa's icy surface.
- Ganymede possesses its own, substantial magnetic field - the first satellite known to have one.
- *Galileo* magnetic data provide evidence that Europa, Ganymede and Callisto have a liquid-saltwater layer under the visible surface.
- Evidence exists that Europa, Ganymede, and Callisto all have a thin atmospheric layer known as a 'surface-bound exosphere'.
- Jupiter's ring system is formed by dust kicked up as interplanetary meteoroids smash into the planet's four small inner moons. The outermost ring is actually two rings, one embedded with the other. There is probably a separate ring along Amalthea's orbit, as well.
- The *Galileo* spacecraft identified the global structure and dynamics of a giant planet's magnetosphere.

Other science conducted with Galileo

The *Galileo* star scanner

The star scanner was a small optical telescope used to provide the spacecraft with an absolute attitude reference. It was also able serendipitously to make scientific discoveries. In the prime mission, it was found that the star scanner was able to detect high energy particles as a noise signal. These data were eventually calibrated to show the particles were predominantly > 2 MeV electrons that were trapped in the Jovian magnetic belts.

A second discovery occurred in 2000. The star scanner was observing a set of stars which included the second magnitude star Delta Velorum. At one point, this star dimmed for 8 hours below the star scanner's detection threshold. Subsequent analysis of *Galileo* data and work by amateur and professional astronomers showed that Delta Velorum is the brightest known eclipsing binary, brighter at maximum than even Algol. It has a primary period of 45 days and the dimming is just visible with the naked eye.

A final discovery occurred during the last two orbits of the mission. When the spacecraft passed the orbit of Jupiter's moon Amalthea, the star scanner detected unexpected flashes of light that were reflections from moonlets. None of the individual moonlets were sighted twice, hence no orbits were determined and the moonlets did not meet the International Astronomical Union requirements to receive designations. It is believed that these moonlets most likely are debris ejected from Amalthea and form a tenuous, and perhaps temporary, ring.

Image taken by *Galileo* of Earth during GOPEX test clearly showing bright laser pulses coming from a transmitting telescope on the night side. *Galileo*'s imager was panned downward during the exposure to separate the pulses, thus blurring earth's image on the right.

Remote detection of life

The late Carl Sagan, pondering the question of whether life on Earth could be easily detected from space, devised a set of experiments in the late 1980s using *Galileo*'s remote sensing instruments to determine if life indeed could be detected during the first Earth flyby of the mission in December 1990. After data acquisition and processing, Sagan et al. published a paper in *Nature* in 1993 detailing the results of the experiment. *Galileo* had found what are now referred to as the "Sagan criteria for life"; these were: strong absorption of light at the red end of the visible spectrum (especially over continents) which was caused by absorption by chlorophyll in photosynthesizing plants, absorption bands of molecular oxygen which is also a result of plant activity, infrared absorption bands caused by the ~1 micromole per mole (µmol/mol) of methane in Earth's atmosphere (a gas which must be replenished by either volcanic or biological activity) and modulated narrowband radio wave transmissions uncharacteristic of any known natural source. *Galileo*'s experiments were thus the first ever controls in the newborn science of astrobiological remote sensing.

The *Galileo* optical experiment

In December 1992 during *Galileo*'s second gravity assist flyby of Earth, another groundbreaking yet almost entirely unpublicized experiment was done using *Galileo* to assess the possibility of optical communication with spacecraft by detecting pulses of light from powerful lasers which were to be directly imaged by *Galileo*'s CCD. The experiment, dubbed Galileo OPtical EXperiment or GOPEX, used two separate sites to beam laser pulses to the spacecraft, one at Table Mountain Observatory in California and the other at the Starfire Optical Range in New Mexico. The Table Mountain site used a frequency doubled Neodymium-Yttrium-Aluminium Garnet (Nd:YAG) laser operating at 532 nm with a repetition rate of ~15 to 30 Hz and a pulse power (FWHM) in the tens of megawatts range, which was coupled to a 0.6 meter Cassegrain telescope for transmission to *Galileo*; the Starfire range site used a similar setup with a larger transmitting telescope (1.5 m). Long exposure (~0.1 to 0.8 s) images using *Galileo's* 560 nm centered green filter produced images of Earth clearly showing the laser pulses even at distances of up to 6,000,000 km. Adverse weather conditions, restrictions placed on laser transmissions by the U.S. Space Defense Operations Center (SPADOC) and a pointing error caused by the scan platform acceleration on the spacecraft being slower than expected (which prevented laser detection on all frames with less than 400 ms exposure times) all contributed to the reduction of the number of successful detections of the laser transmission to 48 of the total 159 frames taken. Nonetheless, the experiment was considered a resounding success and the data acquired will likely be used in the future to design laser "downlinks" which will send large volumes of data very quickly, from spacecraft to Earth. The scheme is already being studied (as of 2004) for a data link to a future Mars orbiting spacecraft.

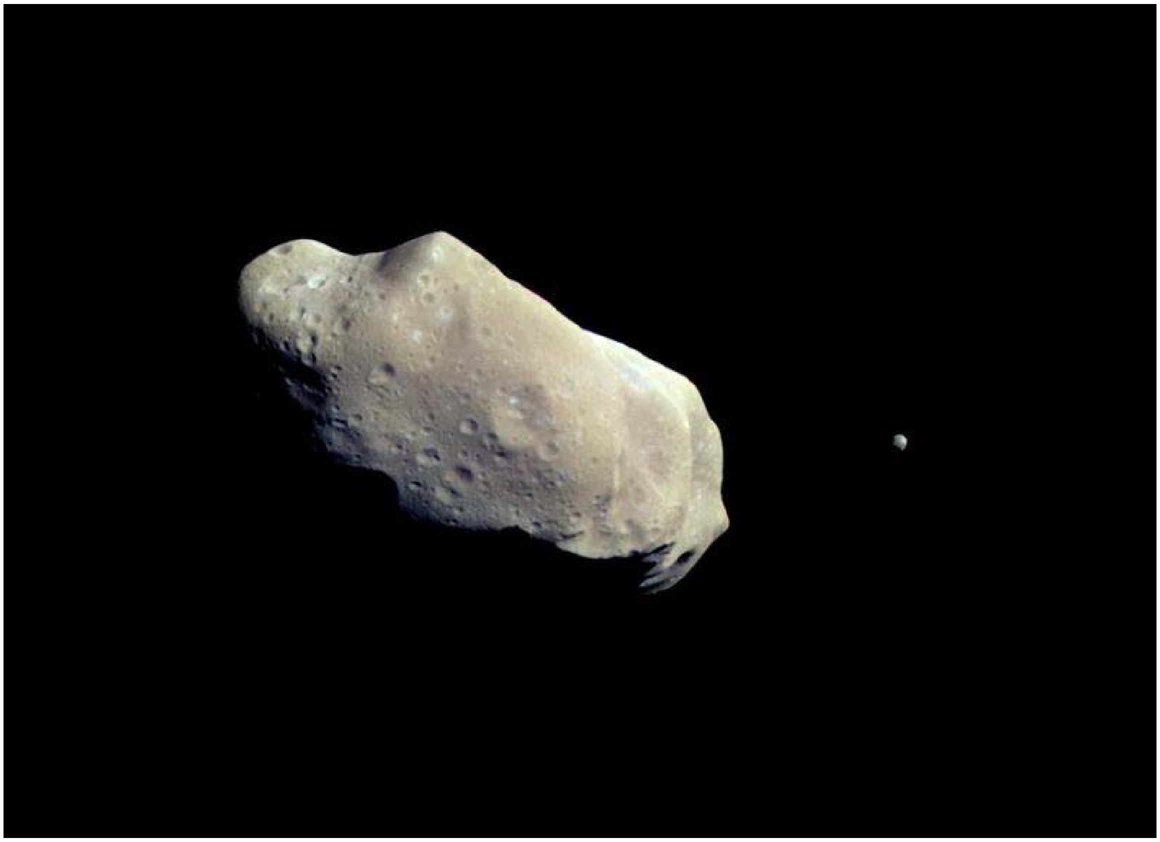
Asteroid encounters

NASA image of 951 Gaspra

First asteroid encounter: 951 Gaspra

On October 29, 1991, two months after entering the asteroid belt, *Galileo* performed the first ever asteroid encounter by passing about 1,600 kilometers (1,000 miles) from 951 Gaspra at a relative speed of about 8 kilometers per second (18,000 mph). Several pictures of Gaspra were taken along with measurements using the NIMS instrument to indicate composition and physical properties. The last (and best) two images were played back to Earth in November 1991 and June 1992. The imagery revealed a cratered and very irregular body about 19 by 12 by 11 kilometers (12 by 7.5 by 7 miles). The remainder of data taken, including low resolution images of more of the surface, were transmitted in late November 1992.

Second asteroid encounter: 243 Ida and Dactyl

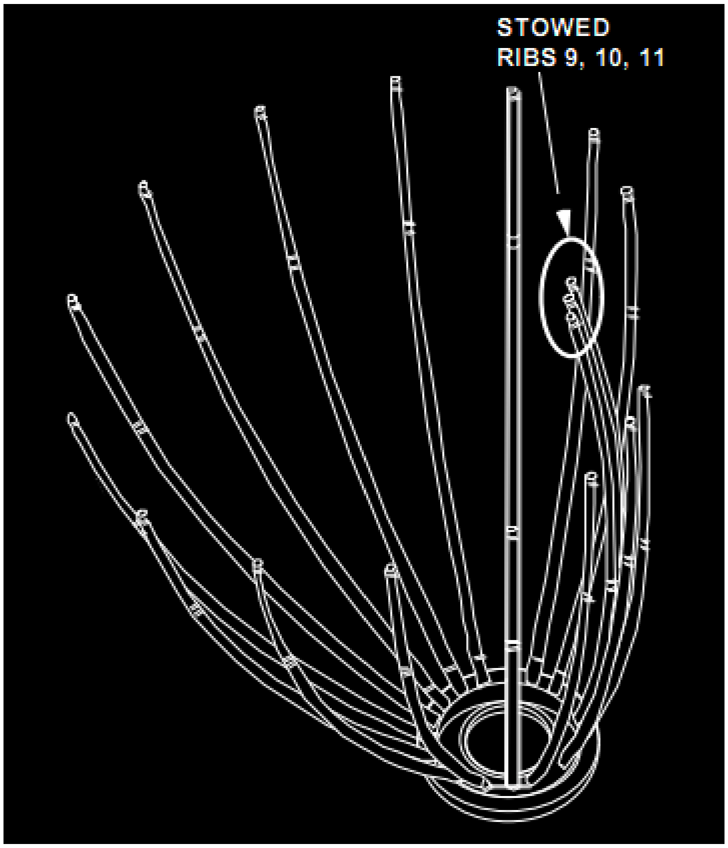


NASA image of 243 Ida. The tiny dot to the right is its moon, Dactyl.

Twenty-two months after the Gaspra encounter, on August 28, 1993, *Galileo* flew within 2,400 kilometers (1,500 miles) of asteroid 243 Ida. The probe discovered that Ida had a small moon, dubbed Dactyl, only 1.4 km in diameter which was the first asteroid moon discovered. Measurements using *Galileo*'s solid state imager, magnetometer and NIMS instrument were taken. From subsequent analysis of data, Dactyl appears to be an SII subtype S type asteroid and is spectrally different from 243 Ida. It is hypothesized that Dactyl may have been produced by partial melting within a Koronis parent body (Ida belongs to the "Koronis" family of asteroids that travels in the main Asteroid Belt between Mars and Jupiter) while the 243 Ida region escaped such igneous processing.

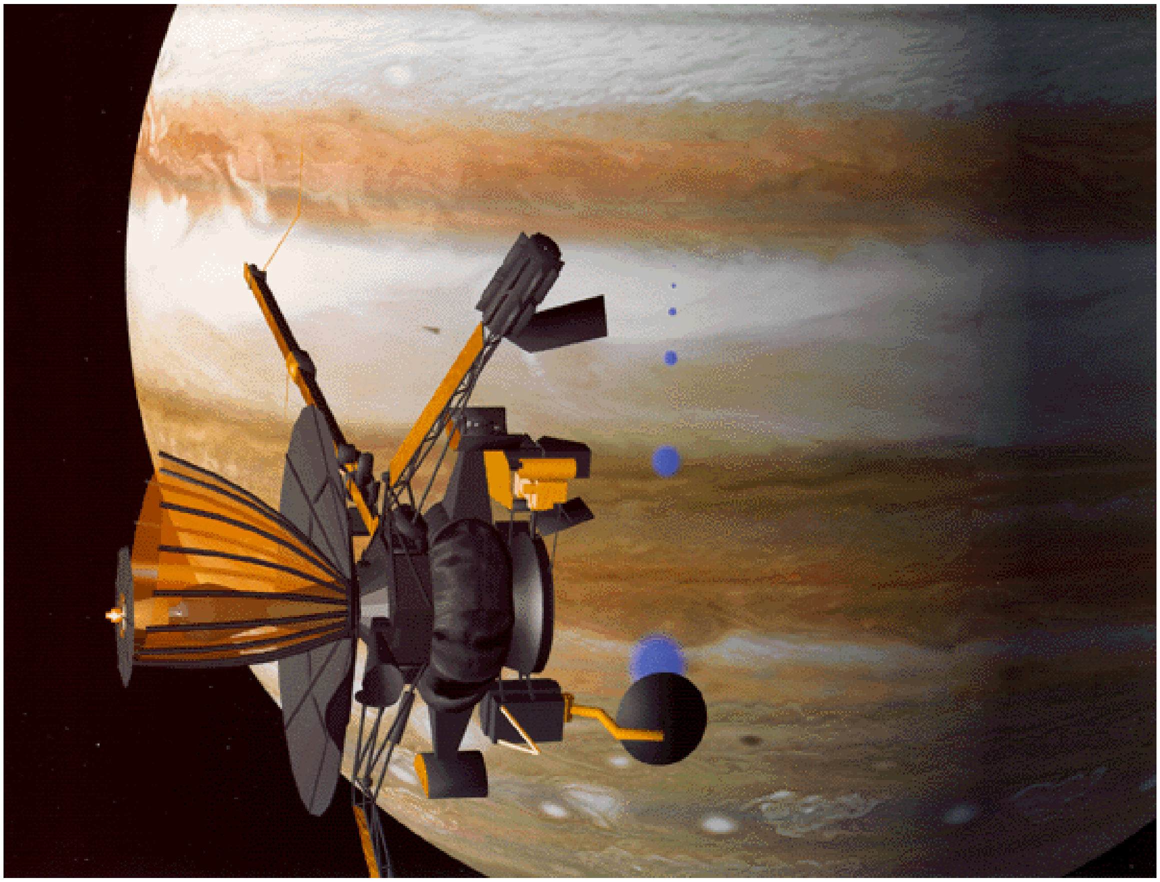
Spacecraft malfunctions

Main antenna failure



Laboratory tests verified that holding ribs 9, 10, and 11 in the stowed position most nearly modeled the spacecraft telemetry.

Artist's concept of *Galileo* at Io. Note the fully deployed high-gain antenna. Compare with below image.


Artist's concept of *Galileo* at Jupiter with only a partially deployed high-gain antenna

For reasons which are not currently known, and in all likelihood will never be known with certainty, *Galileo*'s high-gain antenna failed to fully deploy after its first flyby of Earth. Investigators speculate that during the time that *Galileo* spent in storage after the *Challenger* disaster, the lubricants evaporated, or the system was otherwise damaged. Engineers tried thermal cycling the antenna, rotating the spacecraft up to its maximum spin rate of 10.5 rpm, and "hammering" the antenna deployment motors - turning them on and off repeatedly - over 13,000 times; all attempts failed to open the high-gain antenna. Fortunately *Galileo* had an additional low-gain antenna that was capable of transmitting information back to Earth, though since it transmitted a signal isotropically, the low-gain antenna's bandwidth was significantly less than the high-gain antenna's would have been; the high-gain antenna was to have transmitted at 134 kilobits per second whereas the low-gain antenna was only intended to transmit at about 8 to 16 bits per second. *Galileo*'s low-gain antenna transmitted with a power of about 15 to 20 watts, which, by the time it reached Earth, and had been collected by one of the large aperture (70 m) DSN antennas, had a total power of about -170 dBm or 10 zeptowatts (10×10^{-21} watts). Through implementation of sophisticated data compression techniques, arraying of several Deep Space Network antennas and sensitivity upgrades of receivers used to listen to *Galileo*'s signal, data throughput was increased to a maximum of 160 bits per second. The data collected on Jupiter and its moons was stored in the on board tape recorder, and transmitted back to Earth during the long apozene portion of the probe's orbit using the low-gain antenna. At the same time, measurements were made of Jupiter's magnetosphere and transmitted back to Earth. The reduction in available bandwidth reduced the total amount of data transmitted throughout the mission to about 30 gigabytes and reduced the number of pictures that were transmitted significantly; in all, only around 14,000 images were returned.

Tape recorder anomalies and remote repair

Since *Galileo*'s high-gain antenna failed to open in 1991 the mission was forced to use the low-gain antenna for all communication to Earth. This meant that data storage to *Galileo*'s tape recorder for later compression and playback was absolutely crucial in order to obtain any substantial information from the planned Jupiter and moon flybys. In October 1995, *Galileo*'s 114 megabyte (914,489,344 bits), four-track digital tape recorder which was manufactured by Odetics Corporation, remained stuck in rewind mode for 15 hours before engineers learned what happened and sent commands to shut it off, after recording an image of Jupiter. Though the recorder itself was still in working order the malfunction possibly damaged a length of tape at the end of the reel. This section of tape was subsequently declared "off limits" to any future data recording and was covered with 25 more turns of tape to secure the section and reduce any further stresses, which could tear it. Because it happened only weeks before Jupiter Orbit Insertion, the anomaly prompted engineers to sacrifice data acquisition of almost all of the Io and Europa observations during Jupiter Orbit Insertion in order to focus solely on recording data sent from the Jupiter probe descent.

In November 2002, after completion of the mission's only encounter of Jupiter's moon Amalthea, problems with playback of the tape recorder would again plague the spacecraft. About 10 minutes after closest approach of the flyby *Galileo* stopped collecting data, shut down all of its instruments, and went into safe mode; apparently as a result of exposure to Jupiter's extremely high radiation environment. Though most of the Amalthea data was already written to tape, it was found that the recorder refused to respond to commands telling it to play back data. Through careful analysis after weeks of troubleshooting of an identical flight spare of the recorder on the ground, it was determined that the cause of the malfunction was a reduction of light output in three infrared Optek OP133 light emitting diodes located in the drive electronics of the recorder's motor encoder wheel. The GaAs LEDs had been particularly sensitive to proton irradiation induced atomic lattice displacement defects, which greatly decreased their effective light output and caused the drive motor's electronics to falsely believe the motor encoder wheel was incorrectly positioned. *Galileo*'s flight team then began a series of "annealing" sessions, where current was passed through the LEDs for hours at a time to heat them to a point where some of the crystalline lattice defects would be shifted back into place, thus increasing the LED's light output. After about 100 hours of annealing and playback cycles, the recorder was able to operate for up to an hour at a time. After many subsequent playback and cooling cycles, the complete transmission back to Earth of all recorded Amalthea flyby data was successful.

Other radiation related anomalies

The uniquely harsh radiation environment at Jupiter caused over 20 anomalies in addition to the incidents expanded upon above. Despite exceeding its radiation design limit by at least a factor of three, the spacecraft survived all the anomalies. Several of the science instruments suffered increased noise while within about 700,000 km of Jupiter. The quartz crystal used as the frequency reference for the radio suffered permanent frequency shifts with each Jupiter approach. A spin detector failed and the spacecraft gyro output was biased by the radiation environment. The SSI camera began producing totally white images when the spacecraft was hit by the exceptional 'Bastille Day' coronal mass ejection in 2000 and subsequently on close approaches to Jupiter. The most severe effect was a reset of the computers (a CDS despun bus reset) that occurred when the spacecraft was either close to Jupiter or in the region of space magnetically downstream of the Earth. Work-arounds were found for all of these problems.

Near failure of atmospheric probe parachute

The atmospheric probe deployed its first parachute about one minute later than anticipated, resulting in a small loss of upper atmospheric readings. Through review of records, the problem was later determined to likely be faulty wiring in the parachute control system. The fact that the chute opened at all was attributed to luck.

It is believed today that the accelerometer controlling the parachute's pyrotechnics was installed backwards. The same thing happened to the *Genesis* probe's sample return capsule when it returned to Earth in 2004. In that case, the parachute never opened, and the probe crashed in the desert of Utah.

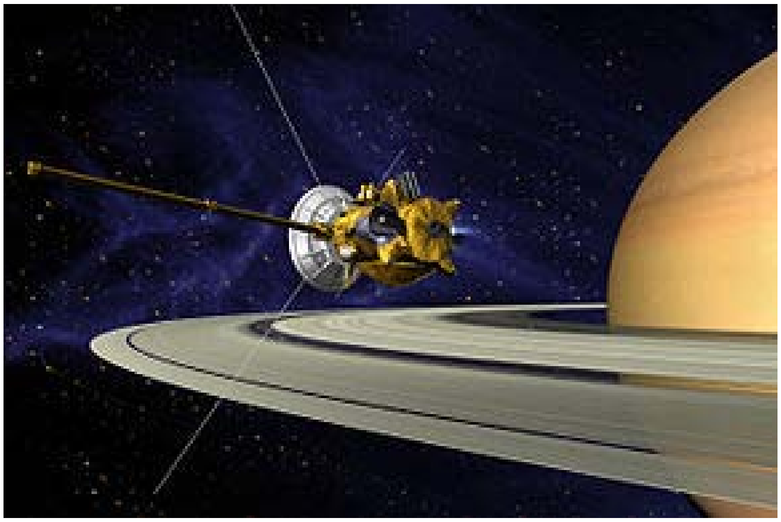
Galileo'*s end*

Once its fuel supply was nearly depleted, *Galileo* was intentionally commanded to crash into Jupiter to eliminate any chance of a future impact with Europa that could contaminate the icy moon. At the completion of its 35th and final circuit around the Jovian system, *Galileo* impacted the gas giant in darkness just south of the equator on September 21, 2003, at 18:57 GMT, at a speed of approximately 48.26 kilometers per second (nearly 108,000 mph). In order to crash into Jupiter, *Galileo* was flown by Amalthea on November 5, 2002, during its 34th orbit, allowing a measurement of the moon's mass as it passed within 163.0 ± 11.7 kilometres (100 mi) of its surface. *Galileo* then reached its greatest distance from Jupiter for the entire mission, some 26 million kilometers on April 14, 2003, before plunging back into the gas giant, taking a little less than nine months to do so.

Chapter- 8

Cassini–Huygens

Cassini–Huygens



Artist's concept of *Cassini*'s Saturn Orbit Insertion maneuver

Operator	NASA / ESA / ASI
Mission type	Flyby, orbiter, lander
Flyby of	Venus, Moon, Earth, Masursky, Jupiter, Saturn's moons
Satellite of	Saturn
Orbital insertion date	2004-07-01 02:48:00 UTC
Launch date	1997-10-15 08:43:00 UTC (13 years, 4 months, and 8 days ago)
Launch vehicle	Titan IV-B / Centaur

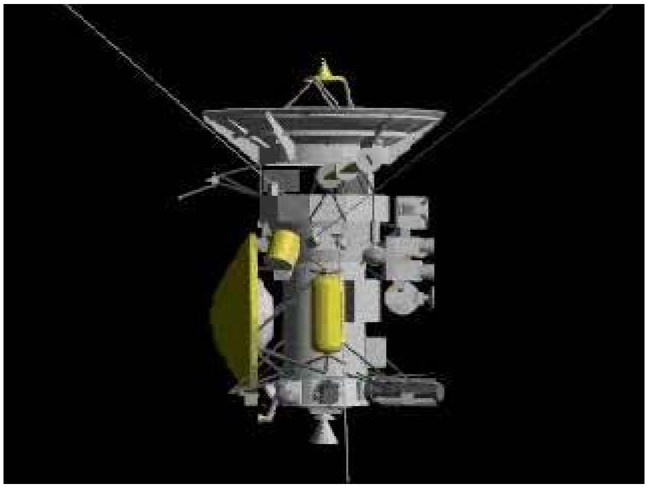
Launch site	Space Launch Complex 40 Cape Canaveral Air Force Station
Mission duration	In Progress (Solstice) (6 years, 7 months, and 22 days elapsed) Venus 1st flyby *(completed 1998-04-26)* Venus 2nd flyby *(completed 1999-06-24)* Moon flyby *(completed 1999-08-18)* Earth flyby *(completed 1999-08-18)* Masursky flyby *(completed 2000-01-23)* Jupiter flyby *(completed 2000-12-30)* Huygens probe *(completed 2005-01-14)* Primary mission *(completed 2008-06-3-30)* Equinox mission *(completed 2010-09-27)*
COSPAR ID	1997-061A
Homepage	saturn.jpl.nasa.gov
Mass	2,523 kg (5,560 lb)
Power	640 W (3 RTGs)

Cassini–Huygens is a joint NASA/ESA/ASI robotic spacecraft mission currently studying the planet Saturn and its many natural satellites. The spacecraft consists of two main elements: the NASA-designed and -constructed *Cassini* orbiter, named for the Italian-French astronomer Giovanni Domenico Cassini, and the ESA-developed *Huygens* probe, named for the Dutch astronomer, mathematician and physicist Christiaan Huygens. The complete *Cassini* space probe was launched on October 15, 1997, and after a long interplanetary voyage it entered into orbit around Saturn on July 1, 2004. On December 25, 2004, the *Huygens* probe was separated from the orbiter at approximately 02:00 UTC. It reached Saturn's moon Titan on January 14, 2005, when it descended into

Titan's atmosphere, and downward to the surface, radioing scientific information back to the Earth by telemetry. This was the first landing ever accomplished in the outer solar system. On April 18, 2008, NASA announced a two-year extension of the funding for ground operations of this mission, at which point it was renamed to **Cassini Equinox Mission**. This was again extended in February 2010 with the mission now continuing until 2017. *Cassini* is the fourth space probe to visit Saturn and the first to enter orbit.

16 European countries and the United States make up the team responsible for designing, building, flying and collecting data from the Cassini orbiter and Huygens probe. The mission is managed by NASA's Jet Propulsion Laboratory in the United States, where the orbiter was designed and assembled. Development of the Huygens Titan probe was managed by the European Space Research and Technology Centre, whose prime contractor for the probe was the Alcatel company in France. Equipment and instruments for the probe were supplied from many countries. The Italian Space Agency (ASI) provided the *Cassini* probe's high-gain radio antenna, and a compact and lightweight radar, which acts in multipurpose as a synthetic aperture radar, a radar altimeter, and a radiometer.

Objectives



Satellite

Cassini has seven primary objectives:

1. Determine the three-dimensional structure and dynamic behavior of the rings of Saturn
2. Determine the composition of the satellite surfaces and the geological history of each object
3. Determine the nature and origin of the dark material on Iapetus's leading hemisphere
4. Measure the three-dimensional structure and dynamic behavior of the magnetosphere
5. Study the dynamic behavior of Saturn's atmosphere at cloud level
6. Study the time variability of Titan's clouds and hazes

7. Characterize Titan's surface on a regional scale

The *Cassini–Huygens* spacecraft was launched on October 15, 1997, from Cape Canaveral Air Force Station's Space Launch Complex 40 using a U.S. Air Force Titan IVB/Centaur rocket. The complete launcher was made up of a two-stage Titan IV booster rocket, two strap-on solid rocket motors, the Centaur upper stage, and a payload enclosure, or fairing.

The total cost of this scientific exploration mission is about US$3.26 billion, including $1.4 billion for pre-launch development, $704 million for mission operations, $54 million for tracking and $422 million for the launch vehicle. The United States contributed $2.6 billion (80%), the ESA $500 million (15%), and the ASI $160 million (5%).

The primary mission for *Cassini* ended on July 30, 2008. However, given the excellent condition of the orbiter, the mission was extended to the end of June 2010 (Cassini Equinox Mission). This studied the Saturn system in detail during Equinox, which happened in August 2009. On February 3, 2010, NASA announced another extension for Cassini, this one for 6½ years until 2017, the time of Summer Solstice in Saturn's Northern Hemisphere (Cassini Solstice Mission). The extension enables another 155 revolutions around the planet, 54 flybys of Titan and 11 flybys of Enceladus. In 2017, an encounter with Titan will change its orbit in such a way that, at closest approach to Saturn, it will be only 3,000km above the planet's cloudtops, below the inner edge of the D ring. This sequence of "proximal orbits" will end when another encounter with Titan sends the probe into Saturn's atmosphere.

History

Launch occurred at 4:43 a.m. EDT (8:43 UTC) on October 15, 1997, from Space Launch Complex 40 at Cape Canaveral Air Force Station, Florida.

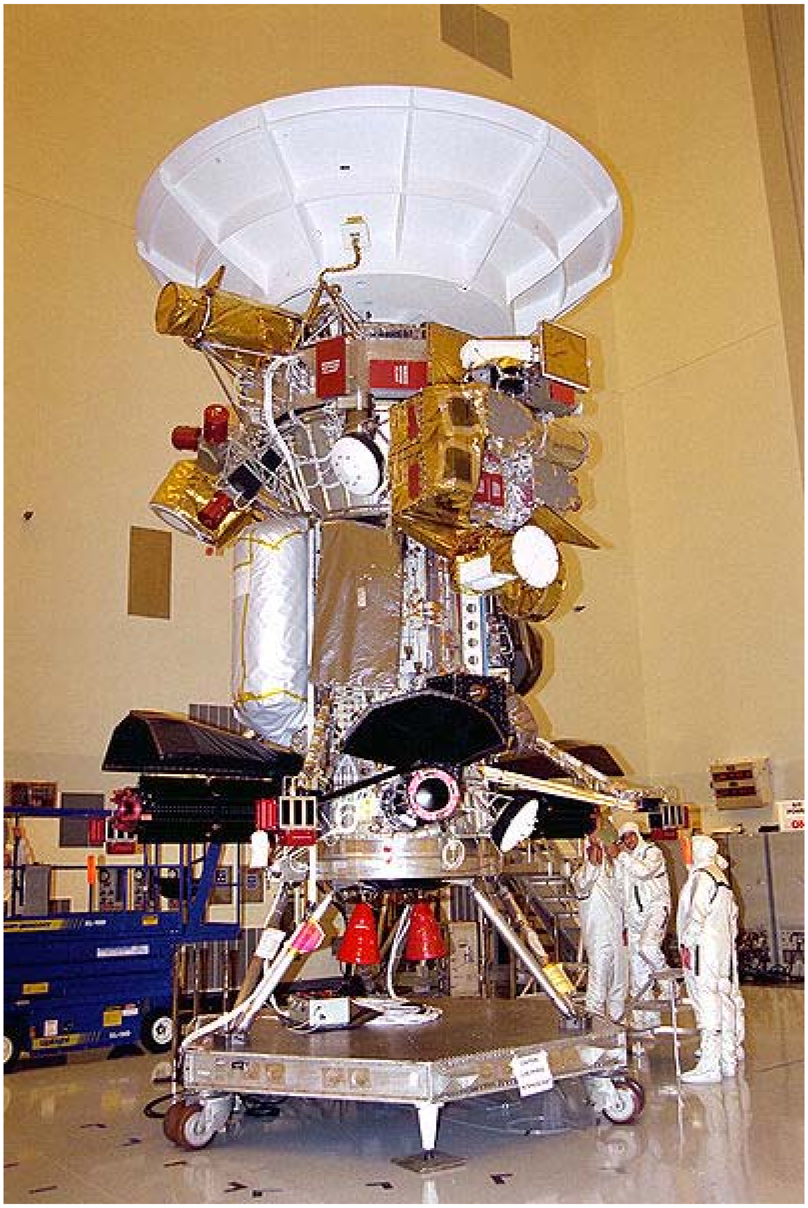
Cassini–Huygens's origins date to 1982, when the European Science Foundation and the American National Academy of Sciences formed a working group to investigate future cooperative missions. Two European scientists suggested a paired Saturn Orbiter and Titan Probe as a possible joint mission. In 1983, NASA's Solar System Exploration Committee recommended the same Orbiter and Probe pair as a core NASA project. NASA and the European Space Agency (ESA) performed a joint study of the potential mission from 1984 to 1985. ESA continued with its own study in 1986, while the American astronaut Sally Ride, in her influential 1987 report "NASA Leadership and America's Future in Space", also examined and approved of the *Cassini* mission.

While Ride's report described the Saturn orbiter and probe as a NASA solo mission, in 1988 the Associate Administrator for Space Science and Applications of NASA Len Fisk returned to the idea of a joint NASA and ESA mission. He wrote to his counterpart at the ESA, Roger Bonnet, strongly suggesting that the ESA choose the *Cassini* mission from the three candidates at hand and promising that NASA would commit to the mission as soon as the ESA did.

At the time, NASA was becoming more sensitive to the strain that had developed between the American and European space programs as a result of European perceptions that NASA had not treated it like an equal during previous collaborations. NASA officials and advisers involved in promoting and planning *Cassini–Huygens* attempted to correct this trend by stressing their desire to evenly share any scientific and technology benefits resulting from the mission. In part, this newfound spirit of cooperation with Europe was driven by a sense of competition with the Soviet Union, which had begun to cooperate more closely with Europe as the ESA drew further away from NASA.

The collaboration not only improved relations between the two space programs but also helped *Cassini–Huygens* survive congressional budget cuts in the United States. *Cassini–Huygens* came under fire politically in both 1992 and 1994, but NASA successfully persuaded the U.S. Congress that it would be unwise to halt the project after the ESA had already poured funds into development because frustration on broken space exploration promises might spill over into other areas of foreign relations. The project proceeded politically smoothly after 1994, although citizens' groups concerned about its potential environmental impact attempted to derail it through protests and lawsuits until and past its 1997 launch.

Spacecraft design



Cassini assembly

The spacecraft was originally planned to be the second three-axis stabilized, RTG-powered Mariner Mark II, a class of spacecraft developed for missions beyond the orbit of Mars. *Cassini* was being developed together with the *Comet Rendezvous Asteroid Flyby* (*CRAF*) spacecraft, but various budget cuts and rescopings of the project forced NASA to terminate *CRAF* development in order to save *Cassini*. As a result, the *Cassini* spacecraft became a more specialized design, canceling the implementation of the Mariner Mark II series.

The spacecraft, including the orbiter and the probe, is the largest and most complex interplanetary spacecraft built to date. The orbiter has a mass of 2,150 kg (4,700 lb), the probe 350 kg (770 lb). With the launch vehicle adapter and 3,132 kg (6,900 lb) of propellants at launch, the spacecraft had a mass of about 5,600 kg (12,000 lb). Only the two Phobos spacecraft sent to Mars by the Soviet Union were heavier. The *Cassini* spacecraft is more than 6.8 meters (22 ft) high and more than 4 meters (13 ft) wide. The complexity of the spacecraft is necessitated both by its trajectory (flight path) to Saturn, and by the ambitious program of scientific observations once the spacecraft reaches its destination. It functions with 1,630 interconnected electronic components, 22,000 wire connections, and over 14 kilometers (8.7 mi) of cabling.

Now that the *Cassini* probe is orbiting Saturn, it is between 8.2 and 10.2 astronomical units from the Earth. Because of this, it takes between 68 to 84 minutes for radio signals to travel from Earth to the spacecraft, and vice-versa. Thus, ground controllers cannot give "real-time" instructions to the spacecraft, either for day-to-day operations, or in cases of unexpected events. Even if they responded immediately after becoming aware of a problem, nearly three hours will have passed between the occurrence of the problem itself and the reception of the engineers' response by the satellite.

Instruments

*Cassini'*s instrumentation consists of: a synthetic aperture radar mapper, a charge-coupled device imaging system, a visible/infrared mapping spectrometer, a composite infrared spectrometer, a cosmic dust analyzer, a radio and plasma wave experiment, a plasma spectrometer, an ultraviolet imaging spectrograph, a magnetospheric imaging instrument, a magnetometer and an ion/neutral mass spectrometer. Telemetry from the communications antenna and other special transmitters (an S-band transmitter and a dual-frequency K_a-band system) will also be used to make observations of the atmospheres of Titan and Saturn and to measure the gravity fields of the planet and its satellites.

Cassini Plasma Spectrometer (CAPS)

> The CAPS is a direct sensing instrument that measures the energy and electrical charge of particles that the instrument encounters, (the amount of electrons and protons in the particle). CAPS will measure the molecules originating from Saturn's ionosphere and also determine the configuration of Saturn's magnetic field. CAPS will also investigate plasma in these areas as well as the solar wind within Saturn's magnetosphere.

Cosmic Dust Analyzer (CDA)

> The CDA is a direct sensing instrument that measures the size, speed, and direction of tiny dust grains near Saturn. Some of these particles are orbiting Saturn, while others may come from other star systems. The CDA on the orbiter is designed to learn more about these mysterious particles, the materials in other celestial bodies and potentially about the origins of the universe.

Composite Infrared Spectrometer (CIRS)

> The CIRS is a remote sensing instrument that measures the infrared waves coming from objects to learn about their temperatures, thermal properties, and compositions. Throughout the Cassini–Huygens mission, the CIRS will measure infrared emissions from atmospheres, rings and surfaces in the vast Saturn

system. It will map the atmosphere of Saturn in three dimensions to determine temperature and pressure profiles with altitude, gas composition, and the distribution of aerosols and clouds. It will also measure thermal characteristics and the composition of satellite surfaces and rings.

Ion and Neutral Mass Spectrometer (INMS)

The INMS is a direct sensing instrument that analyzes charged particles (like protons and heavier ions) and neutral particles (like atoms) near Titan and Saturn to learn more about their atmospheres. INMS is intended also to measure the positive ion and neutral environments of Saturn's icy satellites and rings.

Imaging Science Subsystem (ISS)

The ISS is a remote sensing instrument that captures most images in visible light, and also some infrared images and ultraviolet images. The ISS has taken hundreds of thousands of images of Saturn, its rings, and its moons, for return to the Earth by radio telemetry. The ISS has a wide-angle camera (WAC) that takes pictures of large areas, and a narrow-angle camera (NAC) that takes pictures of small areas in fine detail. Each of these cameras uses a sensitive charge-coupled device (CCD) as its electromagnetic wave detector. Each CCD has a 1,024 square array of pixels, 12 μm on a side. Both cameras allow for many data collection modes, including on-chip data compression. Both cameras are fitted with spectral filters that rotate on a wheel—to view different bands within the electromagnetic spectrum ranging from 0.2 to 1.1 μm.

Dual Technique Magnetometer (MAG)

The MAG is a direct sensing instrument that measures the strength and direction of the magnetic field around Saturn. The magnetic fields are generated partly by the intensely hot molten core at Saturn's center. Measuring the magnetic field is one of the ways to probe the core, even though it is far too hot and deep to visit. MAG aims to develop a three-dimensional model of Saturn's magnetosphere, and determine the magnetic state of Titan and its atmosphere, and the icy satellites and their role in the magnetosphere of Saturn.

Magnetospheric Imaging Instrument (MIMI)

The MIMI is both a direct and remote sensing instrument that produces images and other data about the particles trapped in Saturn's huge magnetic field, or 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 icy satellites.

Radar

The onboard radar is a remote active and remote passive sensing instrument that will produce maps of Titan's surface. It measures the height of surface objects (like mountains and canyons) by sending radio signals that bounce off Titan's surface and timing their return. Radio waves can penetrate the thick veil of haze surrounding Titan. The radar will listen for radio waves that Saturn or its moons may be producing.

Radio and Plasma Wave Science instrument (RPWS)

The RPWS is a direct and remote sensing instrument that receives and measures radio signals coming from Saturn, including the radio waves given off by the interaction of the solar wind with Saturn and Titan. RPWS is to measure the electric and magnetic wave fields in the interplanetary medium and planetary magnetospheres. It will also determine the electron density and temperature near Titan and in some regions of Saturn's magnetosphere. RPWS studies the configuration of Saturn's magnetic field and its relationship to Saturn Kilometric Radiation (SKR), as well as monitoring and mapping Saturn's ionosphere, plasma, and lightning from Saturn's (and possibly Titan's) atmosphere.

Radio Science Subsystem (RSS)

The RSS is a remote sensing instrument that uses radio antennas on Earth to observe the way radio signals from the spacecraft change as they are sent through objects, such as Titan's atmosphere or Saturn's rings, or even behind the Sun. The RSS also studies the compositions, pressures and temperatures of atmospheres and ionospheres, radial structure and particle size distribution within rings, body and system masses and gravitational waves. The instrument uses the spacecraft X-band communication link as well as S-band downlink and K_a-band uplink and downlink.

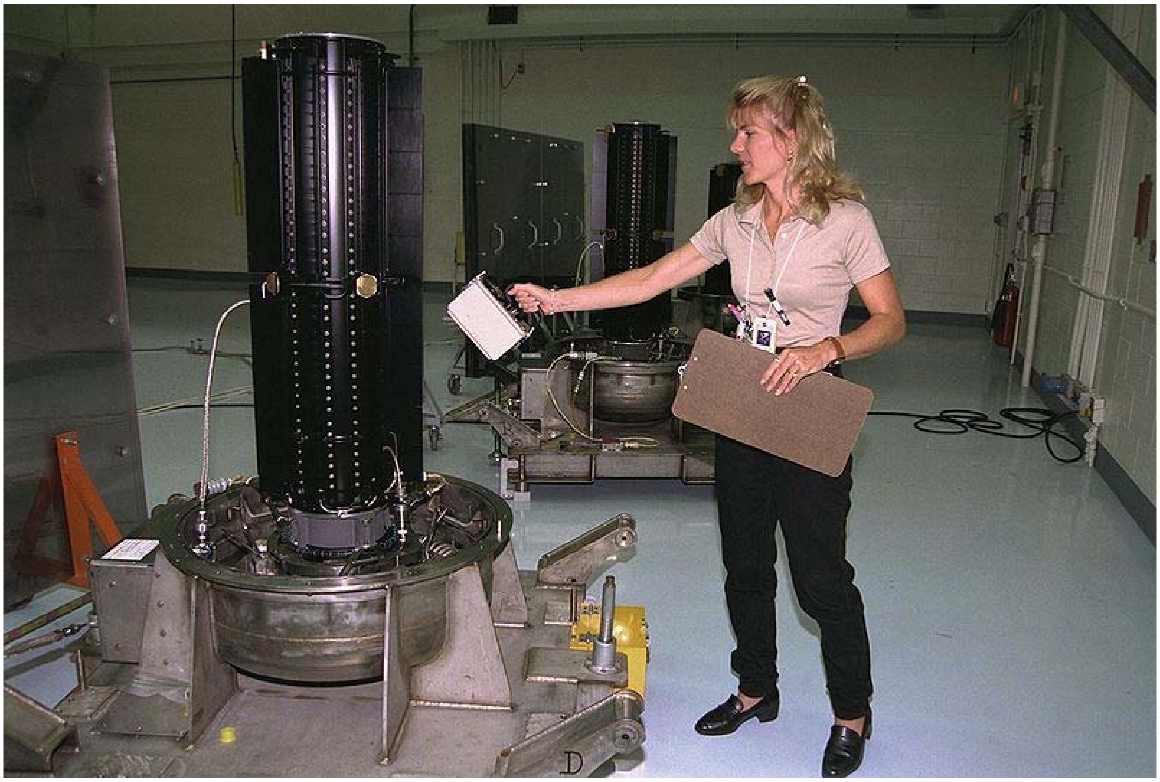
Ultraviolet Imaging Spectrograph (UVIS)

The UVIS is a remote sensing instrument that captures images of the ultraviolet light reflected off an object, such as the clouds of Saturn and/or its rings, to learn more about their structure and composition. Designed to measure ultraviolet light over wavelengths from 55.8 to 190 nm, this instrument is also a valuable tool to help determine the composition, distribution, aerosol particle content and temperatures of their atmospheres. Unlike other types of spectrometer, this sensitive instrument can take both spectral and spatial readings. It is particularly adept at determining the composition of gases. Spatial observations take a wide-by-narrow view, only one pixel tall and 64 pixels across. The spectral dimension is 1,024 pixels per spatial pixel. Also, it can take many images that create movies of the ways in which this material is moved around by other forces.

Visible and Infrared Mapping Spectrometer (VIMS)

The VIMS is a remote sensing instrument that captures images using visible and infrared light to learn more about the composition of moon surfaces, the rings, and the atmospheres of Saturn and Titan. It is made up of two cameras in one: one used to measure visible light, the other infrared. VIMS measures reflected and emitted radiation from atmospheres, rings and surfaces over wavelengths from 350 to 5100 nm, to help determine their compositions, temperatures and structures. It also observes the sunlight and starlight that passes through the rings to learn more about their structure. Scientists plan to use VIMS for long-term studies of cloud movement and morphology in the Saturn system, to determine Saturn's weather patterns.

Plutonium power source



Inspection of *Cassini* spacecraft RTGs before launch

Because of Saturn's distance from the sun, solar arrays were not feasible as power sources for this space probe. To generate enough power, such arrays would have been too large and too heavy. Instead, the *Cassini* orbiter is powered by three radioisotope thermoelectric generators (RTGs), which use heat from the natural decay of plutonium-238 (in the form of plutonium dioxide) to generate direct current electricity via thermocouples. The RTGs on the *Cassini* mission have the same design as those used on the *New Horizons*, *Galileo* and *Ulysses* space probes, and they were designed to have very long operational lifetimes. At the end of the nominal 11-year Cassini mission, they will still be able to produce 600 to 700 watts of electrical power. (One of the spare RTGs for the *Cassini* mission was used to power the New Horizons mission to Pluto and the Kuiper belt, which was designed and launched later on.)

To gain interplanetary momentum while already in flight, the trajectory of the *Cassini* mission included several gravitational slingshot maneuvers: two fly-by passes of Venus, one more of the Earth, and then one of the planet Jupiter. The terrestrial fly-by was the final instance when the *Cassini* space probe posed any conceivable danger to human beings. This occurred successfully, with hundreds of miles to spare (the space probe passing 500 km above the Earth), on August 18, 1999. Had there been any malfunction that caused the *Cassini* space probe to collide with the Earth, NASA's complete environmental impact study estimated that, in the worst case (with an acute angle of entry in which *Cassini* would gradually burn up), a significant fraction of the 32.7 kg of plutonium-238 inside the RTGs would have been dispersed into the Earth's atmosphere so that up to five billion people could have been exposed, causing an estimated 500,000 cancer deaths, but the odds against that happening were nearly ten million to one.

Huygens *probe*

The *Huygens* probe, supplied by the European Space Agency (ESA) and named after the 17th century Dutch astronomer who first discovered Titan, Christiaan Huygens, scrutinized the clouds, atmosphere, and surface of Saturn's moon Titan in its descent on January 15, 2005. It was designed to enter and brake in Titan's atmosphere and parachute a fully instrumented robotic laboratory down to the surface.

The probe system consisted of the probe itself which descended to Titan, and the probe support equipment (PSE) which remained attached to the orbiting spacecraft. The PSE includes electronics that track the probe, recover the data gathered during its descent, and process and deliver the data to the orbiter that transmits it to Earth. The data was transmitted by a radio link between *Huygens* and *Cassini* provided by Probe Data Relay Subsystem (PDRS). As the probe's mission could not be telecommanded from Earth because of the great distance, it was automatically managed by the Command Data Management Subsystem (CDMS). The PDRS and CDMS were provided by the Italian Space Agency (ASI).

Important events and discoveries

Venus and Earth fly-bys and the cruise to Jupiter

Picture of the Moon during flyby

The *Cassini* space probe performed two gravitational-assist fly-bys of Venus on April 26, 1998, and June 24, 1999. These fly-bys provided the space probe with enough momentum to travel all the way out to the asteroid belt. At that point, the sun's gravity pulled the space probe back into the inner solar system, where it made a gravitational-assist fly-by of the Earth.

On August 18, 1999, at 03:28 UTC, the *Cassini* craft made a gravitational-assist flyby of the Earth. One hour and 20 minutes before closest approach, *Cassini* made the closest approach to the Earth's Moon at 377,000 kilometers, and it took a series of calibration photos.

On Jan. 23, 2000, the *Cassini* space probe performed a fly-by of the asteroid 2685 Masursky at around 10:00 UTC. The *Cassini* craft took photos in the period five to seven hours before the fly-by at a distance of 1.6 million kilometers, and a diameter of 15 to 20 km was estimated for the asteroid.

Jupiter flyby

Jupiter flyby picture

Cassini made its closest approach to Jupiter on December 30, 2000, and made many scientific measurements. About 26,000 images of Jupiter were taken during the months-long flyby. It produced the most detailed global color portrait of Jupiter yet, in which the smallest visible features are approximately 60 km (40 miles) across.

The *New Horizons* mission to Pluto captured more recent images of Jupiter, with a closest approach on February 28, 2007.

A major finding of the flyby, announced on March 6, 2003, was of Jupiter's atmospheric circulation. Dark "belts" alternate with light "zones" in the atmosphere, and scientists had long considered the zones, with their pale clouds, to be areas of upwelling air, partly because many clouds on Earth form where air is rising. But analysis of *Cassini* imagery showed that individual storm cells of upwelling bright-white clouds, too small to see from Earth, pop up almost without exception in the dark belts. According to Anthony Del Genio of NASA's Goddard Institute for Space Studies, "the belts must be the areas of net-rising atmospheric motion on Jupiter, [so] the net motion in the zones has to be sinking."

Other atmospheric observations included a swirling dark oval of high atmospheric-haze, about the size of the Great Red Spot, near Jupiter's north pole. Infrared imagery revealed aspects of circulation near the poles, with bands of globe-encircling winds, with adjacent bands moving in opposite directions.

The same announcement also discussed the nature of Jupiter's rings. Light scattering by particles in the rings showed the particles were irregularly shaped (rather than spherical) and likely originate as ejecta from micrometeorite impacts on Jupiter's moons, probably Metis and Adrastea.

Tests of Einstein's Theory of General Relativity

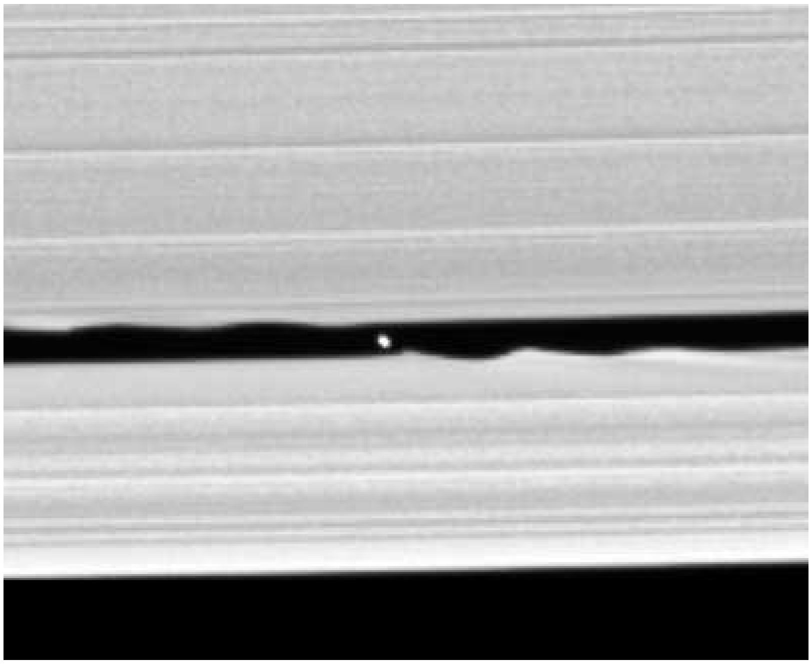
On October 10, 2003, the *Cassini* science team announced the results of tests of Einstein's Theory of General Relativity, which were done by using radio waves that were transmitted from the *Cassini* space probe.

The radio scientists measured a frequency shift in the radio waves to and from the spacecraft, while those signals traveled close to the sun. According to the Theory of General Relativity, a massive object like the sun causes space-time to curve, and a beam of radio waves (or light, or any form of electromagnetic radiation) that passes by the sun has to travel farther because of the curvature.

The extra distance that the radio waves traveled from the *Cassini* craft, past the sun, to the Earth delays their arrival. The amount of this time delay provides a sensitive test of the calculated predictions of Einstein's Relativity Theory.

Although some measurable deviations from the values that are calculated using the General Theory of Relativity are predicted by some unusual cosmological models, none of these deviations were found by this experiment. Previous tests using radio waves that were transmitted by the *Viking* and *Voyager* space probes were in agreement with the calculated values from General Relativity to within an accuracy of one part in one thousand. The more refined measurements from the *Cassini* space probe experiment improved this accuracy to about one part in 50,000, with the measured data firmly supporting Einstein's General Theory of Relativity.

New moons of Saturn



Discovery photograph of moon Daphnis

Using images taken by *Cassini*, three new moons of Saturn were discovered in 2004. They are very small and were given the provisional names S/2004 S 1, S/2004 S 2 and S/2004 S 5 before being named Methone, Pallene and Polydeuces at the beginning of 2005.

On May 1, 2005, a new moon was discovered by *Cassini* in the Keeler gap. It was given the designation S/2005 S 1 before being named Daphnis. The only other known moon inside Saturn's ring system is Pan.

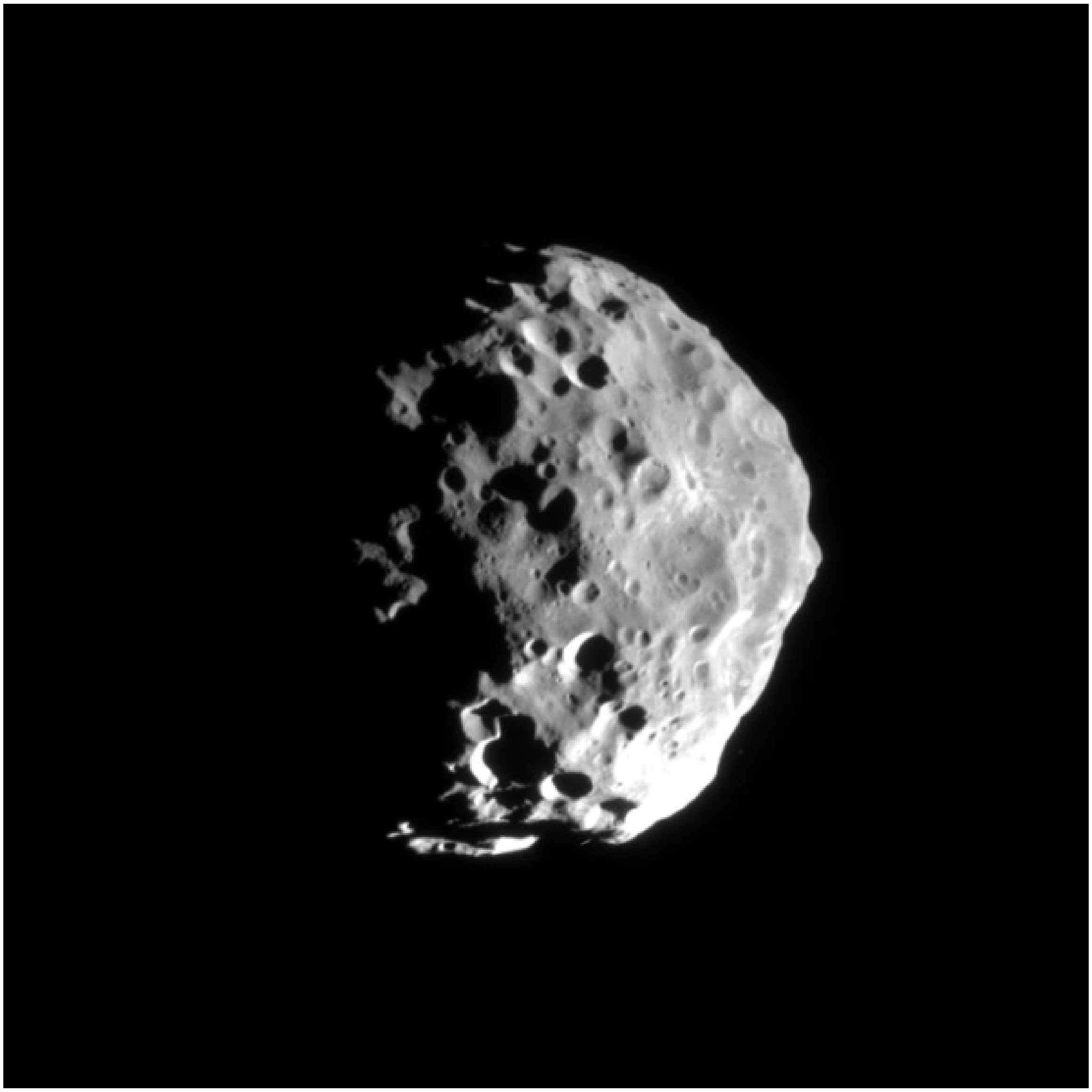


Image of Phoebe

A press release on February 3, 2009 shows yet a 6th new moon found by the Cassini Spacecraft. The moon is approximately 1/3 of a mile long in the G-ring of the ring system of Saturn, now named Aegaeon.

A press release on November 2, 2009 mentions the 7th new moon found by the Cassini Spacecraft on July 26, 2009. It is presently labeled S/2009 S 1 and is approximately 300 m (984 ft.) in diameter in the B-ring system.

Phoebe flyby

On June 11, 2004, *Cassini* flew by the moon Phoebe. This was the first opportunity for close-up studies of this moon since the *Voyager 2* flyby. It also was *Cassini*'s only possible flyby for Phoebe due to the mechanics of the available orbits around Saturn.

First close-up images were received on June 12, 2004, and mission scientists immediately realized that the surface of Phoebe looks different from asteroids visited by spacecraft. Parts of the heavily cratered surfaces look very bright in those pictures, and it is currently believed that a large amount of water ice exists under its immediate surface.

Saturn rotation

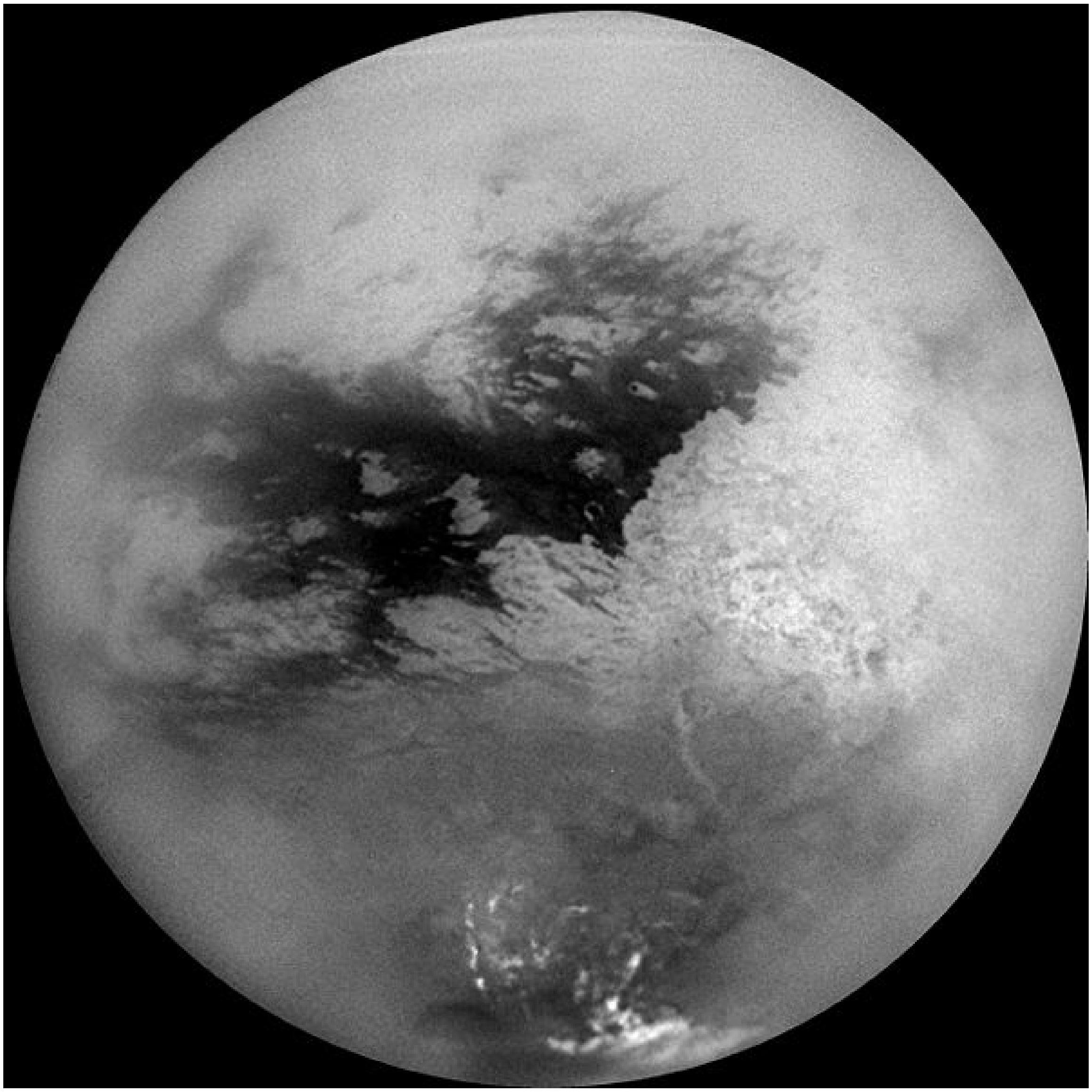
In an announcement on June 28, 2004, *Cassini* program scientists described the measurement of the rotational period of Saturn. Since there are no fixed features on the surface that can be used to obtain this period, the repetition of radio emissions was used. These new data agree with the latest values measured from Earth, and constitute a puzzle to the scientists. It turns out that the radio rotational period has changed since it was first measured in 1980 by *Voyager*, and that it is now 6 minutes longer. This does not indicate a change in the overall spin of the planet, but is thought to be due to movement of the source of the radio emissions to a different latitude, at which the rotation rate is different.

Orbiting Saturn

On July 1, 2004, the spacecraft flew through the gap between the F and G rings and achieved orbit, after a seven year voyage. It is the first spacecraft to ever orbit Saturn.

The Saturn Orbital Insertion (SOI) maneuver performed by *Cassini* was complex, requiring the craft to orient its High-Gain Antenna away from Earth and along its flight path, to shield its instruments from particles in Saturn's rings. Once the craft crossed the ring plane, it had to rotate again to point its engine along its flight path, and then the engine fired to decelerate the craft by 622 meters per second to allow Saturn to capture it. *Cassini* was captured by Saturn's gravity at around 8:54 p.m. Pacific Daylight Time on June 30, 2004. During the maneuver *Cassini* passed within 20,000 km (13,000 miles) of Saturn's cloud tops.

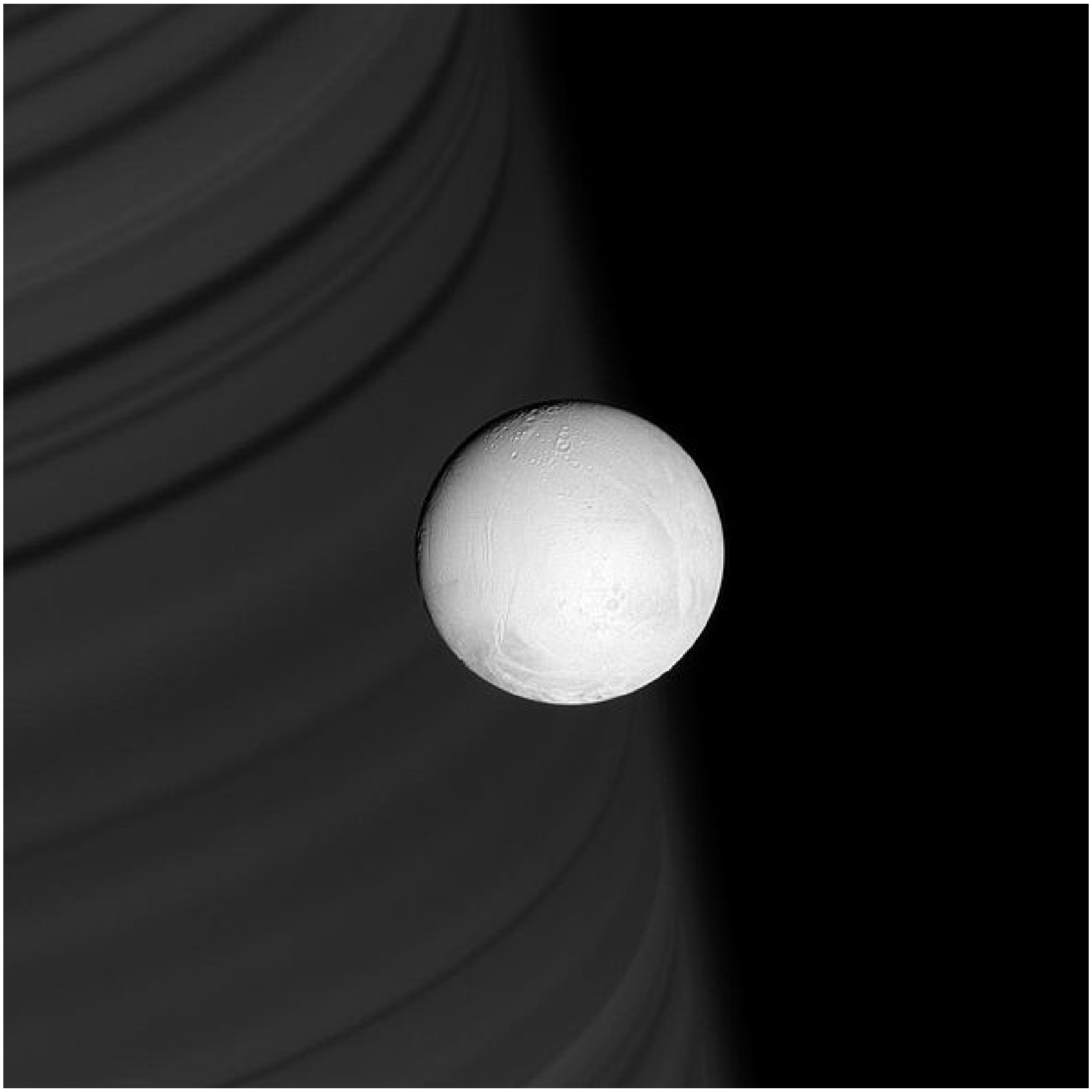
Titan flybys



Titan's surface

Cassini had its first distant flyby of Saturn's largest moon, Titan, on July 2, 2004, only a day after orbit insertion, when it approached to within 339,000 km (211,000 mi) of Titan and provided the best look at the moon's surface to date. Images taken through special filters showed south polar clouds thought to be composed of methane and surface features with widely differing brightness. On October 27, 2004, the spacecraft executed the first of the 45 planned close flybys of Titan when it flew a mere 1,200 kilometers above the moon. Almost four gigabits of data were collected and transmitted to Earth, including the first radar images of the moon's haze-enshrouded surface. It revealed the surface of Titan (at least the area covered by radar) to be relatively level, with topography reaching no more than about 50 meters in altitude. The flyby provided a remarkable increase in imaging resolution over previous coverage. Images with up to 100 times better "resolution" were taken and are typical of resolutions planned for subsequent Titan flybys. (Note that "resolution" refers to the clarity and precision of pictures, and that it has nothing to do with the overall size of the pictures in square centimeters, as is very commonly erroneously stated.)

***Huygens'* encounter with Titan**



Enceladus backdropped by Saturn's ring shadows

Cassini released the *Huygens* probe on December 25, 2004, by means of a spring. It entered the atmosphere of Titan on January 14, 2005, and after a two-and-a-half-hour descent landed on solid ground with no liquids in view. Although Cassini successfully relayed 350 of the pictures that it received from Huygens of its descent and landing site, a software error failed to turn on one of the Cassini receivers and caused the loss of the other 350 pictures.

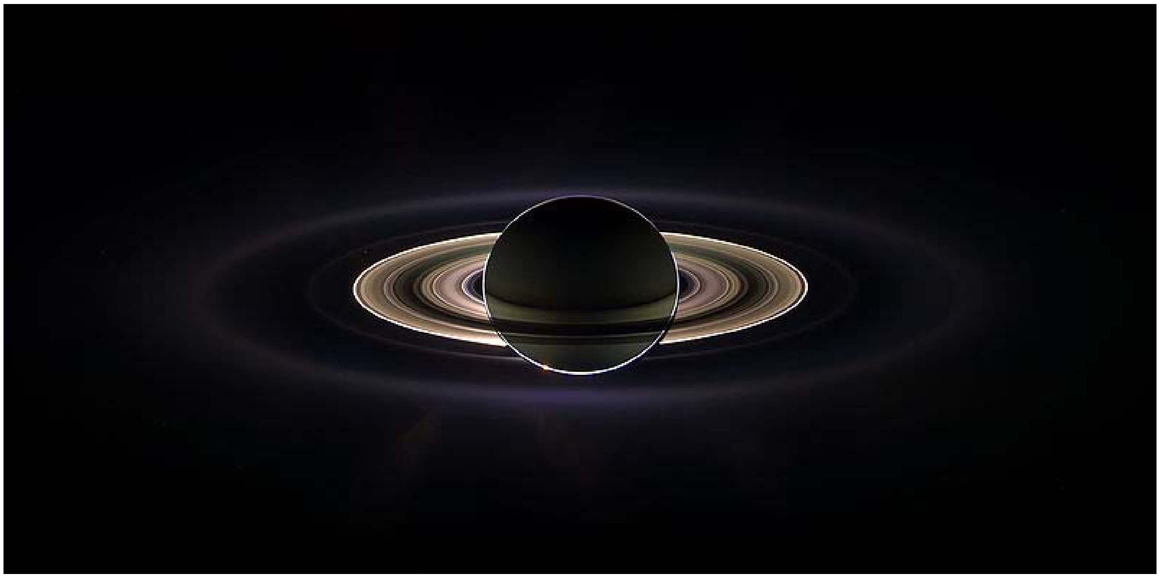
Enceladus flybys

During the first two close flybys of the moon Enceladus in 2005, *Cassini* discovered a "deflection" in the local magnetic field that is characteristic for the existence of a thin but significant atmosphere. Other measurements obtained at that time point to ionized water vapor as being its main constituent. *Cassini* also observed water ice geysers erupting from the south pole of Enceladus, which gives more credibility to the idea that Enceladus is supplying the particles of Saturn's E ring. Mission scientists hypothesize that there may be pockets of liquid water near the surface of the moon that fuel the eruptions, making Enceladus one of the few bodies in our solar system to contain liquid water.

On March 12, 2008, *Cassini* made a close fly-by of Enceladus, getting within 50 km of the moon's surface. The spacecraft passed through the plumes extending from its southern geysers, detecting water, carbon dioxide and various hydrocarbons with its mass spectrometer, while also mapping surface features that are at much higher temperature than their surroundings with the infrared spectrometer. *Cassini* was unable to collect data with its cosmic dust analyzer due to an unknown software malfunction.

On November 21 Cassini again made a fly by of Enceladus, this time with a very different geometry, approaching within 1,600 kilometers (1000 miles) of the surface. The Composit Infrared Spectrograph (CIRS) instrument will make a map of thermal emissions from the tiger stripe Baghdad Sulcus. This is the eighth flyby of Enceladus and is also sometimes referred to as “E-8.” The data and images returned will help to create the most-detailed-yet mosaic image of the southern part of the moon's Saturn-facing hemisphere and a contiguous thermal map of one of the intriguing "tiger stripe" features, with the highest resolution to date.

Radio occultations of Saturn's rings



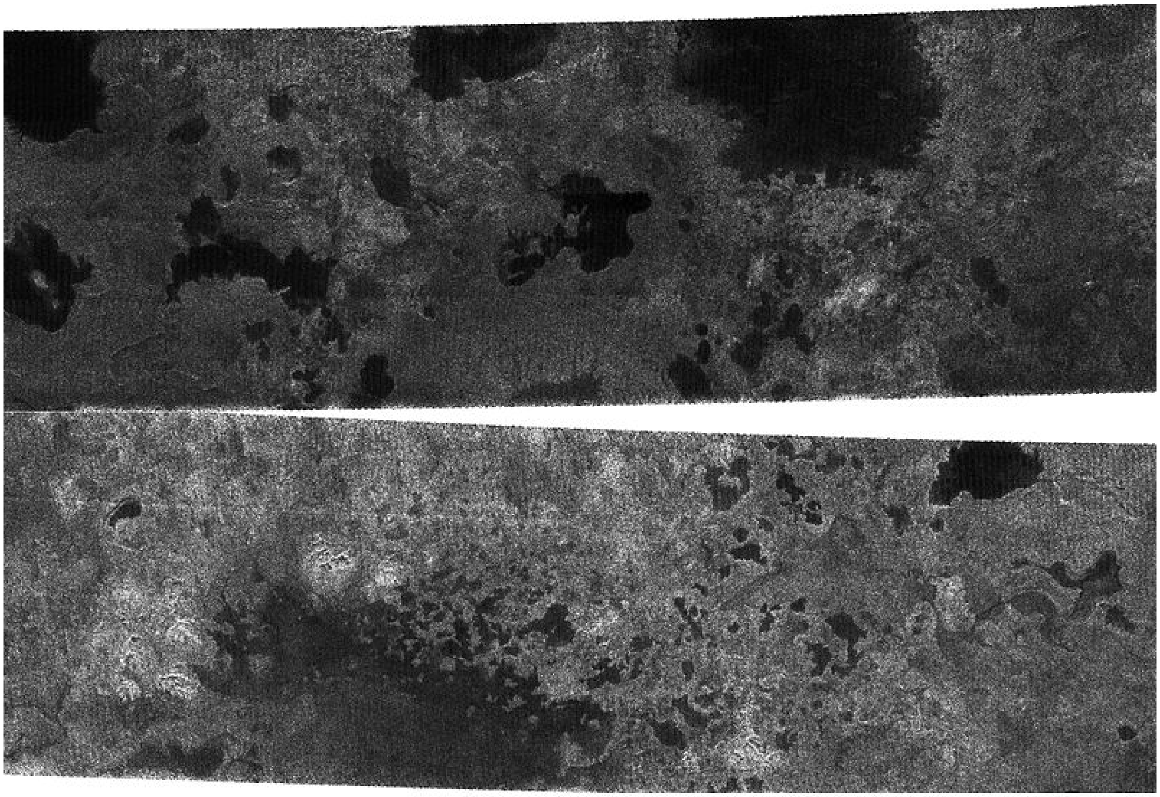
An eclipse of Saturn with the rings visible, taken in 2006

In May 2005, *Cassini* began a series of occultation experiments, to measure the size-distribution of particles in Saturn's rings, and measure the atmosphere of Saturn itself. For over 4 months, *Cassini* completed orbits designed for this purpose. During these experiments, *Cassini* flew behind the ring plane of Saturn, as seen from Earth, and transmitted radio waves through the particles. The radio signals were received on Earth, where the frequency, phase, and power of the signal was analyzed to help determine the structure of the rings.

Spoke phenomenon verified

In images captured September 5, 2005, *Cassini* detected spokes in Saturn's rings, previously seen only by the visual observer Stephen James O'Meara in 1977 and then confirmed by the *Voyager* space probes in the early 1980s.

Lakes of Titan



Lakes of Titan

Radar images obtained on July 21, 2006 appear to show lakes of liquid hydrocarbon (such as methane and ethane) in Titan's northern latitudes. This is the first discovery of currently-existing lakes anywhere besides Earth. The lakes range in size from about a kilometer to one which is one hundred kilometers across.


Titan "sea" (left) compared at scale to Lake Superior (right)

On March 13, 2007, the Jet Propulsion Laboratory announced that it found strong evidence of seas of methane and ethane in the northern hemisphere of Titan. At least one of these is larger than any of the Great Lakes in North America.

Saturn hurricane

In November 2006, scientists discovered a storm at the south pole of Saturn with a distinct eyewall. This is characteristic of a hurricane on Earth and had never been seen on another planet before. Unlike a terran hurricane, the storm appears to be stationary at the pole. The storm is 8,000 kilometers (5,000 mi) across, and 70 kilometres (43 mi) high, with winds blowing at 560 kilometers per hour (350 mph).

Iapetus flyby

On September 10, 2007, *Cassini* completed its flyby of the strange, two-toned, walnut-shaped moon, Iapetus. Images were taken from 1,000 miles (1,600 km) above the surface. As it was sending the images back to Earth, it was hit by a cosmic ray which forced it to temporarily enter safe mode. All of the data from the flyby was recovered.

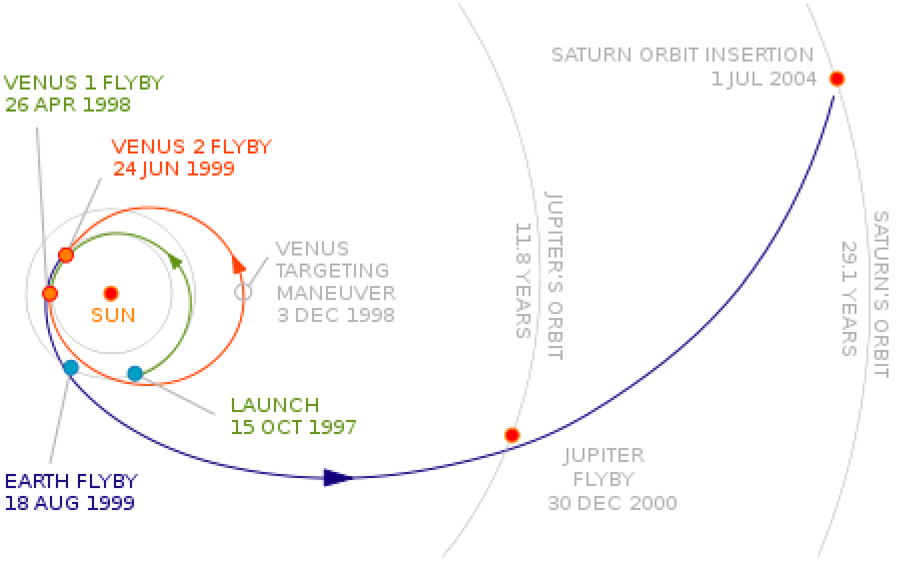
Mission extension

On April 15, 2008, Cassini received funding for a two-year extended mission. It consists of 60 more orbits of Saturn, and includes 21 more Titan flybys, seven of Enceladus, six of Mimas, eight of Tethys, and one targeted flyby each of Dione, Rhea, and Helene. The extended mission began on July 1, 2008, and has since been renamed the Cassini Equinox Mission as the mission coincides with Saturn's equinox. A proposal was submitted to

NASA for a second mission extension, provisionally named the extended-extended mission or XXM. This was subsequently approved and renamed the Cassini Solstice Mission. It will see Cassini orbiting Saturn 155 more times, conducting 54 additional flybys of Titan and 11 more of Enceladus. The mission will end with a fiery plunge into the Saturn atmosphere around its 2017 northern summer solstice, safely disposing of the spacecraft without risk of biocontamination to the Saturnian moons.

On November 2, 2010, Cassini was triggered into a protective standby mode, or "safe mode", after a bit flip caused it to miss an important instruction. NASA announced the interruption in scientific processes on November 8. However, by November 8 some of the craft's functionality had already been partly restored. Nominal scientific instrument sequencing events were successfully started on November 10. Cassini was reactivated as scheduled on November 24 and has returned to perfect working order, in time for two scheduled close fly-bys with Enceladus. At this point there has been no public disclosure as to the data loss impact of the November 11 (T-73) flyby. However, no images were acquired at the 11 November polar flyby.

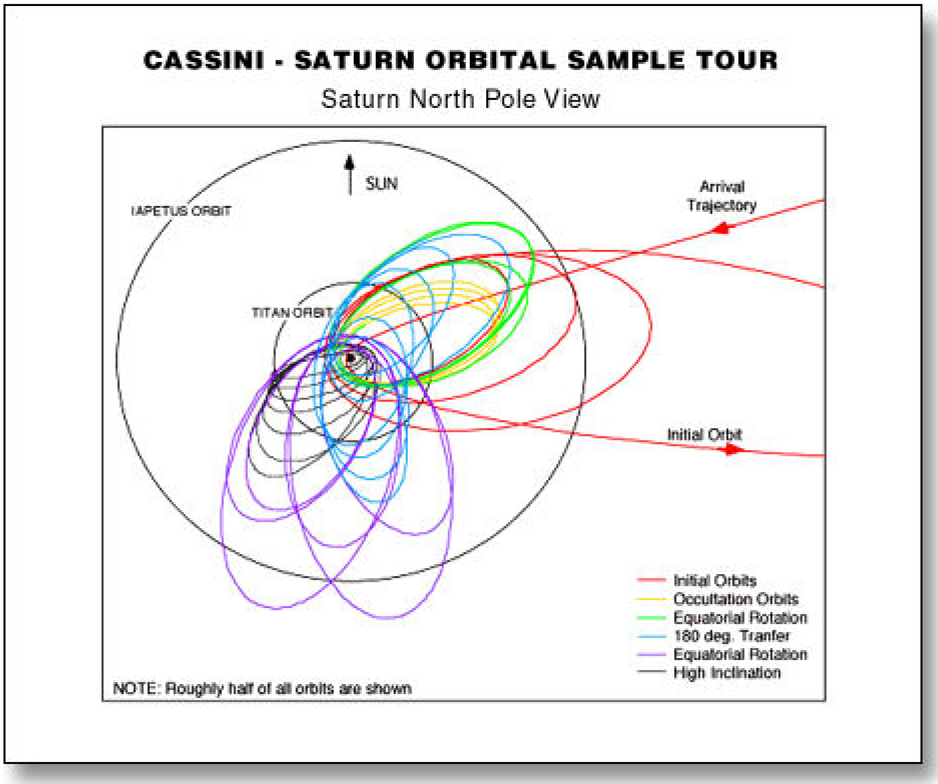
Trajectory



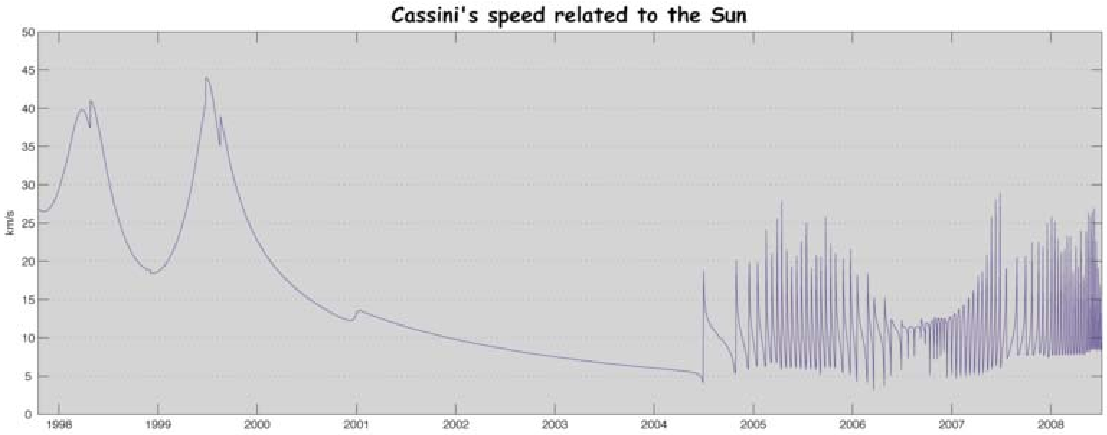
The initial gravitational-assist trajectory of *Cassini–Huygens*

The initial gravitational-assist trajectory of *Cassini–Huygens* is the process whereby an insignificant mass approaches a significant mass "from behind" and "steals" some of its orbital momentum. The significant mass, usually a planet, loses a very small proportion of its orbital momentum to the insignificant mass, the space probe in this case. However, due to the space probe's small mass, this momentum transfer gives it a relatively large momentum increase in proportion to its initial momentum, speeding up its travel through outer space.

The *Cassini–Huygens* space probe performed two gravitational assist fly-bys at Venus, one more fly-by at the Earth, and a final fly-by at Jupiter.



Simplified diagram which shows, in two dimensions, the orbital motion of *Cassini–Huygens* on and after arrival at Saturn



The *Cassini* craft's speed relative to the Sun. The various gravitational slingshots form visible peaks on the left, while the periodic variation on the right is caused by the spacecraft's orbit around Saturn. The data came from the JPL Horizons Ephemeris System in 2005. The speed above is instantaneous velocity in kilometers per second. The date/time is UTC in Spacecraft Event Time, which is from 1997-Oct-16 00:00:01 to 2008-Jul-06 23:59:59 UTC, with two leap seconds during this period. Note also that the minimum velocity achieved during its Saturnian orbit is more or less equal to Saturn's own orbital velocity, which is the ~5.0 km/sec. velocity which the *Cassini* craft matched to enter orbit!

Chapter- 9

Lunar-A & LEO

Lunar-A

LUNAR-A	
Operator	JAXA
Mission type	Orbiter, impactor
Satellite of	The Moon
Launch date	Cancelled
Carrier rocket	M-5
COSPAR ID	LUNAR-A
Homepage	LUNAR-A page
Mass	520 kg
Orbital elements	
Inclination	30°
Apoapsis	200 km
Periapsis	300 km
Orbital period	2h

LUNAR-A is a cancelled Japanese spacecraft project that was originally scheduled to be launched in August 2004. After many delays (primarily due to potential thruster faults , the project was eventually cancelled in January 2007. It has been planned to be launched on a Japanese M-V rocket from the Kagoshima Space Center.

The vehicle would have been cylindrical, with a diameter of 2.2 m and a height of 1.7 m. It would have had four solar panels and was engineered to be spin-stabilized. Plans called for it to enter an elliptical orbit around the Moon, and deploy two penetrators at an altitude of 40 km on opposite sides of the lunar body. The penetrators were to have been braked by a small rocket at an altitude of 25 km, then free fall to the surface. They were designed to withstand a collision speed of 330 meters per second to deeply penetrate the lunar regolith.

Once the penetrators deployed, the LUNAR-A spacecraft was mission-planned to maneuver to an orbital altitude of 200 km above the lunar surface. The craft was to have carried a monochromatic imaging camera with a resolution of 30 m.

LEO (spacecraft)

LEO - Lunar Exploration Orbiter

Operator	German Aerospace Center
Mission type	Orbiter
Satellite of	**Moon**
Launch date	2012
Mission duration	4 years
Mass	ca. 650 kg (Main- and sub-satellite)
	Orbital elements
Periapsis	50 km

LEO (**L**unarer **E**rkundungs**o**rbiter - engl.: Lunar Exploration Orbiter) is the name of a proposed, but currently indefinitely postponed, German mission to the Moon, announced by the German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt e.V.*) Director Walter Doellinger on March 2, 2007.

Precise characteristics of the mission were announced in early 2008, and estimated costs are €350 million (~$514 million) over five years, however the mission will involve a lunar orbiter that DLR intends to build and launch in 2012 to map the lunar surface.

It would be the first German mission to the Moon and the first European mission to the Moon since SMART-1.

Because the needed money for the year 2009 will not be available on time, the start of the project was delayed indefinitely.

Numerous leading German planetologists, among them Gerhard Neukum, Ralf Jaumann and Tilman Spohn, have condemned the indefinite postponement and argue for resuming the LEO-project.

Design

The main satellite will weigh about 500 kilograms and is accompanied by a small sub-satellite, which weighs about 150 kilograms. The intended orbital altitude is about 50 km.

Experiments will measure lunar gravitational and magnetic fields.

The main satellite will carry a microwave radar to probe beneath the lunar surface up to a depth of a few hundred meters. At maximum depth the radar will be able to resolve structures up to two meters.

Science objectives

The duration of the mission around the Moon will be four years, during which the entire surface will be charted for the first time. The survey is to be three-dimensional and in colour.

"The probe will examine the moon's surface and provide indications of significant geological formations that could later be of interest for drilling," Doellinger said.

The probe will also investigate the moon's magnetic and gravity fields, look for water and analyse the minerals on its surface. It will use the best camera currently available, the best radar sensors and unique spectrum sensors for measuring the mineral composition.