Past Individual Space Exploration Missions

Nita Lipscomb

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Table of Contents

Chapter- 1

Magellan (Spacecraft)

Magellan

Artist depiction of Magellan at Venus.

Operator	NASA / CNES
Mission type	Orbiter
Satellite of	Venus
Orbital insertion date	1990-08-10 17:00:00 UTC
Launch date	1989-05-04 18:47:00 UTC (21 years, 9 months, and 15 days ago)
Launch vehicle	Space Shuttle Atlantis (STS-30) Inertial Upper Stage
Launch site	Launch Complex 39B, Kennedy Space Center

Mission duration	August 10, 1990 - October 12, 1994 (deorbited 1994-10-12)
COSPAR ID	1989-033B
Homepage	Magellan Mission to Venus
Mass	1,035 kg (2,282 lb)
Power	1029 W (Solar array / NiCad)

The **Magellan spacecraft** was an American space probe sent to the planet Venus, the first unmanned interplanetary spacecraft to be launched by NASA since its successful *Pioneer Orbiter*, also to Venus, in 1978. It was also the first of three deep-space probes to be launched on the Space Shuttle (the others being the Ulysses Sun probe and the Galileo spacecraft to Jupiter) until the launching of the failed Mars Observer spacecraft on a Titan III rocket in 1992, and the first spacecraft to employ aerobraking techniques to circularize its orbit, a technique used on the current series of orbiters around Mars that allows fuel to be conserved.

Magellan created the first (and currently the best) near-photographic quality, high resolution radar mapping of the planet's surface features. Prior Venus missions had created low resolution radar globes of general, continent-sized formations. Magellan, however, finally allowed detailed imaging and analysis of craters, hills, ridges, and other geologic formations, to a degree comparable to the visible-light photographic mapping of other planets. Magellan's global radar map will remain the most detailed Venus map in existence for the foreseeable future, although the planned Russian Venera-D may carry a radar that can achieve the same, if not better resolution as the radar used by Magellan.

It was named after the sixteenth-century Portuguese explorer Ferdinand Magellan. Magellan was the first planetary spacecraft to be launched by a Space Shuttle when it was carried aloft by the Orbiter *Atlantis* from Kennedy Space Center in Florida on May 4, 1989, on the STS-30 mission. *Atlantis* took Magellan into low Earth orbit, where it was released from the shuttle's cargo bay. A solid-fuel motor, the Inertial Upper Stage (IUS) then fired, sending Magellan on a 15-month cruise looping around the Sun 1-1/2 times before it arrived at its orbit around Venus on August 10, 1990. In 1994 it plunged to the surface as planned and partly vaporized; some sections are thought to have hit the planet's surface.

Mission overview

Magellan's initial orbit was highly elliptical, taking it as close as 294 kilometers (182 miles) from Venus and as far away as 8,543 km (5,296 mi). The orbit was a polar one, meaning that the spacecraft moved from south to north or vice versa during each looping pass, flying over Venus' north and south poles. Magellan completed one orbit every 3 hours, 15 minutes.

During the part of its orbit closest to Venus, Magellan's radar mapper imaged a swath of the planet's surface approximately 17 to 28 km (10 to 17 mi) wide. At the end of each orbit, the spacecraft radioed back to Earth a map of a long ribbon-like strip of the planet's surface captured on that orbit. Venus itself rotates once every 243 Earth days. As the planet rotated under the spacecraft, Magellan collected strip after strip of radar image data, eventually covering the entire globe at the end of the 243-day orbital cycle.

By the end of its first such eight-month orbital cycle between September 1990 and May 1991, Magellan had sent to Earth detailed images of 84 percent of Venus' surface. The spacecraft then conducted radar mapping on two more eight-month cycles from May 1991 to September 1992. This allowed it to capture detailed maps of 98 percent of the planet's surface. The follow-on cycles also allowed scientists to look for any changes in the surface from one year to the next. In addition, because the "look angle" of the radar was slightly different from one cycle to the next, scientists could construct three-dimensional views of Venus' surface.

During Magellan's fourth eight-month orbital cycle at Venus from September 1992 to May 1993, the spacecraft collected data on the planet's gravity field. During this cycle, Magellan did not use its radar mapper but instead transmitted a constant radio signal to

Earth. If it passed over an area of Venus with higher than normal gravity, the spacecraft would slightly speed up in its orbit. This would cause the frequency of Magellan's radio signal to change very slightly due to the Doppler effect – much like the pitch of a siren changes as an ambulance passes. Thanks to the ability of radio receivers in the NASA/JPL Deep Space Network to measure frequencies extremely accurately, scientists could build up a detailed gravity map of Venus.

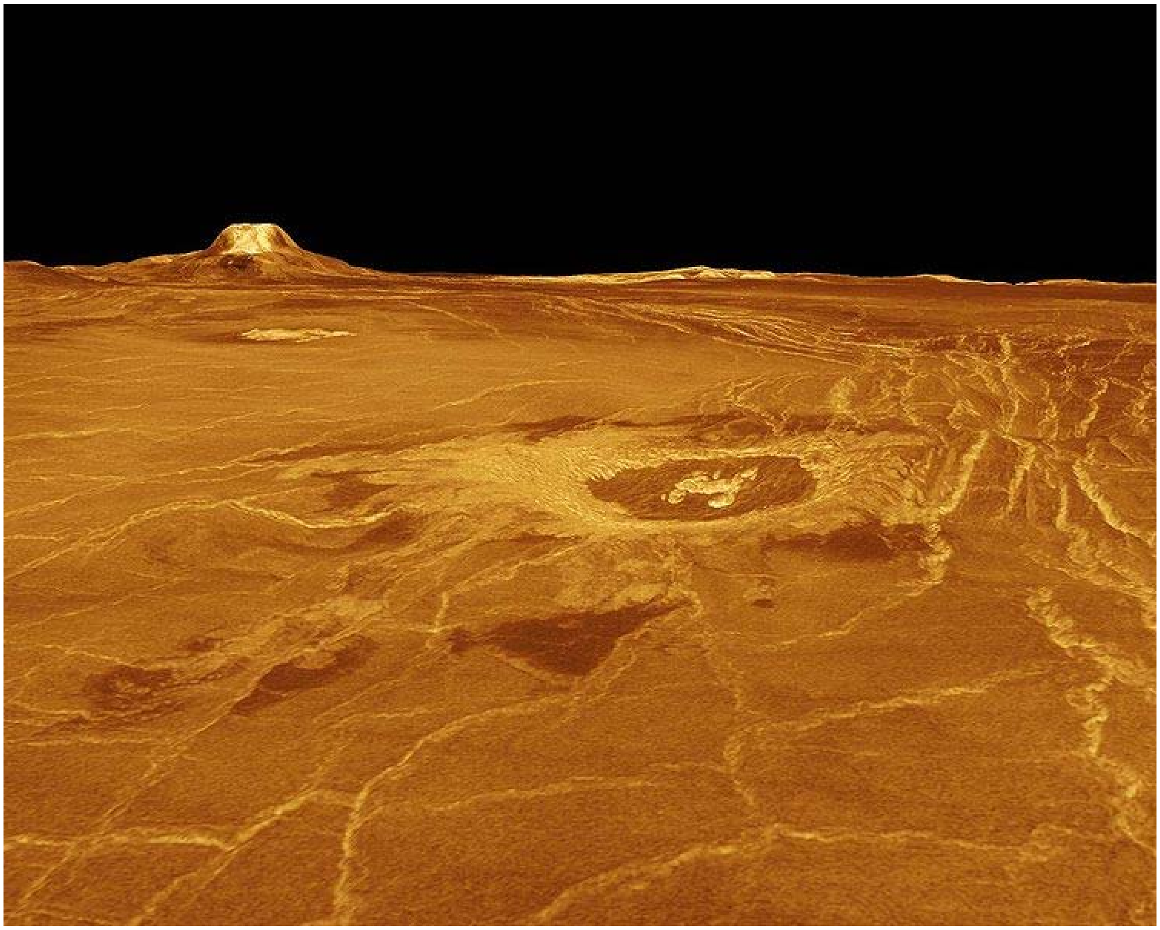
At the end of Magellan's fourth orbital cycle in May 1993, flight controllers circularized the spacecraft's orbit using a then-untried technique called aerobraking. This maneuver sent Magellan dipping into Venus' atmosphere once every orbit; the atmospheric drag on the spacecraft slowed down Magellan and lowered its periapsis. After the aerobraking was completed between May 25 and August 3, 1993, Magellan's orbit then took it as close as 180 km (112 mi) from Venus and as far away as 541 km (336 mi). Magellan also circled Venus more quickly, completing an orbit once every 94 minutes (roughly the same amount of time its takes the Space Shuttle or the International Space Station to complete a single orbit around Earth). This new, more circularized orbit allowed Magellan to collect better gravity data in the higher northern and southern latitudes near Venus' poles.

After the end of that fifth orbital cycle in April 1994, Magellan began a sixth and final orbital cycle, collecting more gravity data and conducting radar and radio science experiments. By the end of the mission, Magellan had captured high-resolution gravity data for an estimated 95 percent of the planet's surface.

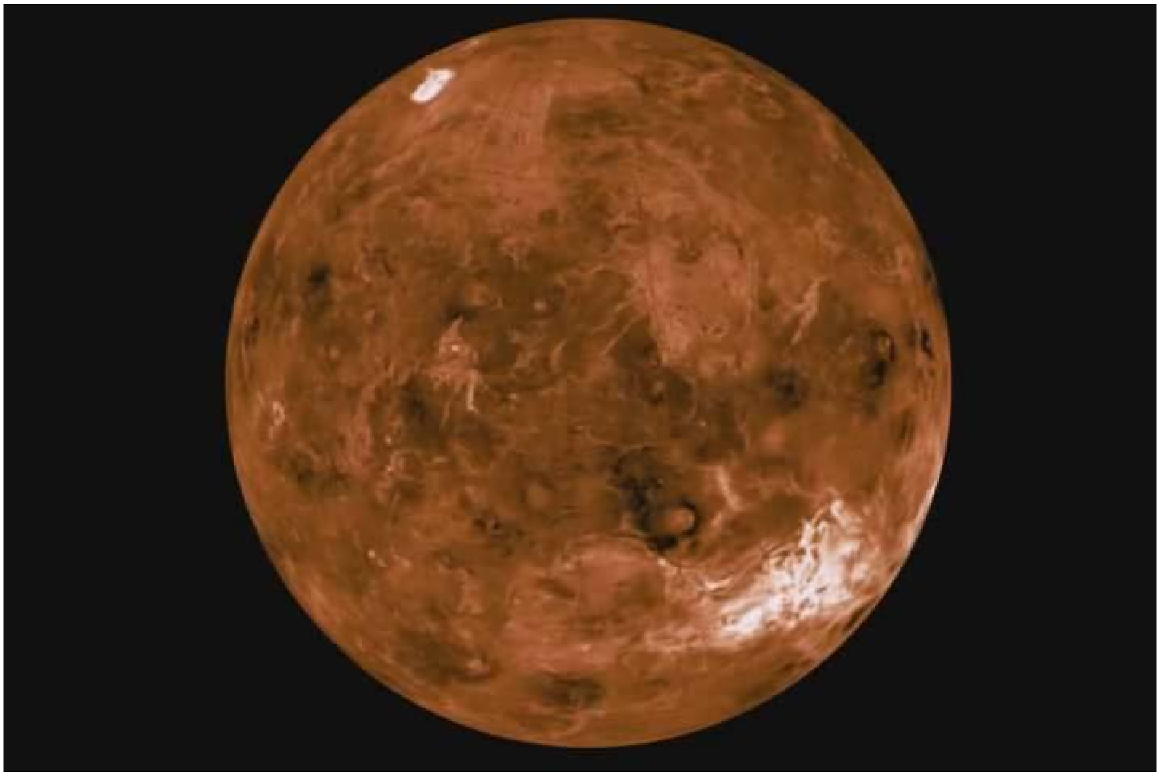
In September 1994, Magellan's orbit was lowered once more in another test called a "windmill experiment". In this test, the spacecraft's solar panels were turned to a configuration resembling the blades of a windmill, and Magellan's orbit was lowered into the thin outer reaches of Venus' dense atmosphere. Flight controllers then measured the amount of torque control required to maintain Magellan's orientation and keep it from spinning. This experiment gave scientists data on the behaviour of molecules in Venus' upper atmosphere, and lead engineers new information useful in designing spacecraft.

On October 11, 1994, Magellan's orbit was lowered a final time and radio contact was lost the next day. Within two days after that maneuver, the spacecraft became caught in the atmosphere and plunged to the surface. Although much of Magellan was vaporized, some sections are thought to have hit the planet's surface intact.

Imaging cycles



3D view of Venus's Eistla Regio produced from *Magellan* radar data.



Rendered image of Venus rotating using data gathered by Magellan.

From its arrival in August, 1990 until its demise in 1994, the Magellan spacecraft's primary mission was divided into "imaging cycles," each lasting 243 days total (the time it takes Venus to complete a single rotation on its axis). During each of the early cycles, the probe would complete a total of 7.3 orbits for each Earth day, imaging strips approximately 17 to 28 km. (11 to 17 mi.) wide and 70,000 km. (43,486 mi.) long. It took a total of 1,800 strips to cover the entire planet, which were then combined into a single mosaic image.

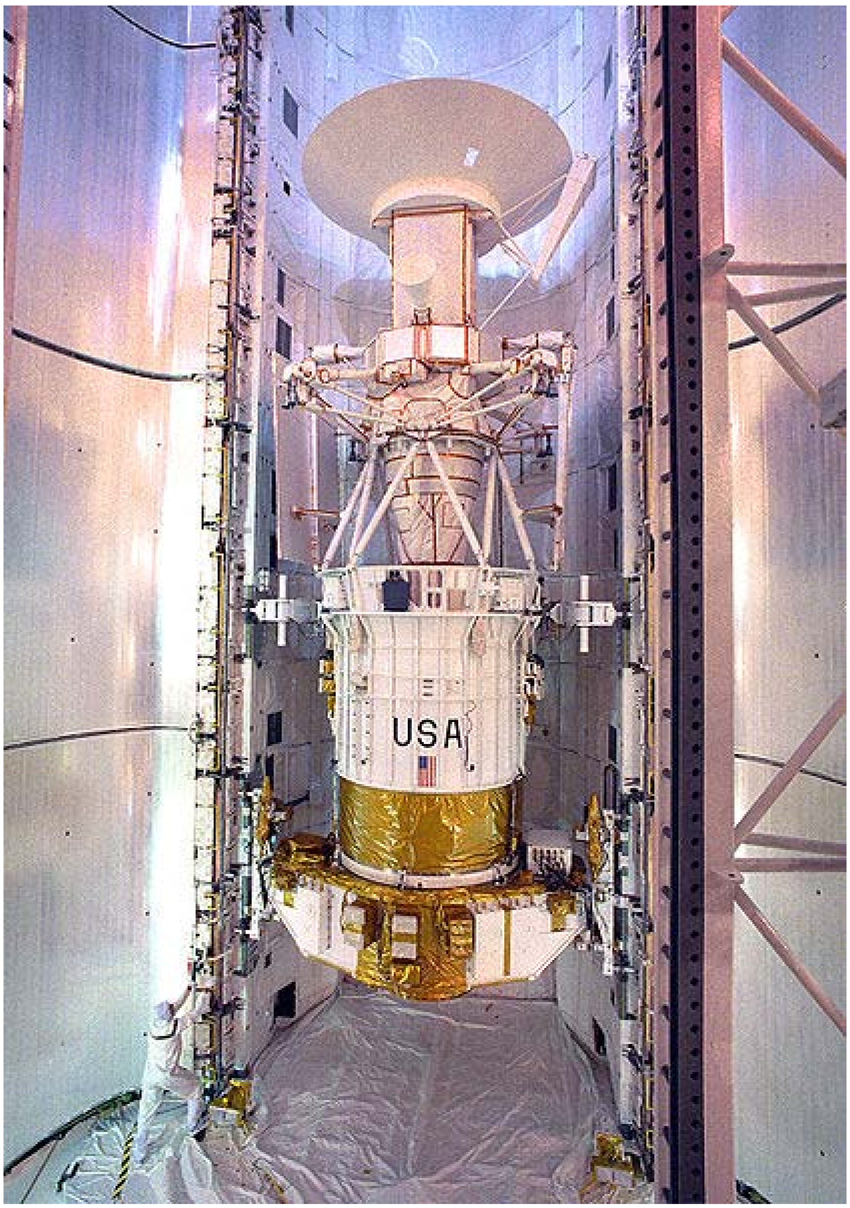
The first images of Venus were received on August 16, 1990, and routine mapping operations began on September 15, 1990. The first mapping cycle (Cycle 1) was completed successfully on May 15, 1991, mapping 84% of the Venusian surface.

Cycle 2 began immediately afterwards and lasted until January 15, 1992. In each cycle, the probe was inclined at a different "look angle", producing stereoscopic data which enabled scientists to compile a three-dimensional map of the surface—a technique known as interferometric synthetic aperture radar.

Cycle 3 was due to finish on September 14, 1992, but was terminated a day early due to problems with onboard equipment. In total, radar coverage of 98% of the surface of Venus was obtained, with 22% of the images in stereo. *Magellan* produced surface images of unprecedented clarity and coverage, which are still unsurpassed.

Cycles 4, 5 and 6 were devoted to collecting gravimetric data, for which *Magellan* was aerobraked to its lowest possible stable orbit, with a periapsis or closest approach of 180 kilometers (112 mi). At the end of Cycle 6 its orbit was reduced further, entering the outer reaches of the atmosphere. After carrying out a few final experiments, *Magellan* successfully completed its mission on October 11, 1994, and was de-orbited to burn up in Venus's atmosphere.

Spacecraft design



The Magellan spacecraft being fixed into position inside the Space Shuttle Atlantis payload bay prior to launch.

Built largely from spare parts from both the *Voyager* and *Galileo* missions, the Magellan spacecraft was 4.6 meters (15.4 feet) long, topped with a 3.7 m (12 ft) parabolic antenna. Mated to its solid rocket motor (which was jettisoned after orbital insertion) and fully tanked with propellants, the spacecraft weighed a total of 3,460 kilograms (7,612 pounds) at launch.

The high-gain antenna, used for both communication and radar imaging, was a spare from the Voyager Program to the outer planets, as were Magellan's 10-sided main bus section and a set of thrusters. On board computer systems, and power distribution units are spares from the Galileo mission to Jupiter. and its medium-gain antenna is from the NASA/JPL Mariner 9 project. Martin Marietta Astronautics (Now Lockheed Martin) was the prime contractor for the Magellan spacecraft, while Hughes Space & Communications was the prime contractor for the radar system.

Magellan was powered by two square solar panels, each measuring 2.5 m (8.2 ft) on a side; together they supplied 1,200 watts of power (100 watt per m^2). Over the course of the mission the solar panels gradually degraded, as expected; by the end of the mission in the fall of 1994 it was necessary to manage power usage carefully to keep the spacecraft operating.

Because Venus was shrouded by a dense, opaque atmosphere, conventional optical cameras could not be used to image its surface. Instead, Magellan's imaging radar used bursts of microwave energy somewhat like a camera flash to illuminate the planet's surface.

Magellan's high-gain antenna sent out thousands of pulses each second toward the planet; the antenna then collected the echoes returned to the spacecraft when the radar pulses bounce off Venus' surface. Because the radar pulses were not sent directly downward but rather at a slight angle to the side of the spacecraft, the radar is thus sometimes called "side-looking radar". In addition, special processing techniques were used on the radar data to result in higher resolution as if the radar had a larger antenna, or "aperture"; the technique is thus often called "synthetic aperture radar", or SAR. Magellan's maps had an ultimate resolution of about 120m; the published maps are oversampled at 75m.

Synthetic aperture radar was first used by NASA on JPL's Seasat oceanographic satellite in 1978; it was later developed more extensively on the Spaceborne Imaging Radar (SIR) missions on the space shuttle in 1981, 1984 and 1994. An imaging radar was also used as part of the NASA/JPL Cassini mission to Saturn in 1997 to map the surface of the ringed planet's major moon Titan.

Besides its use in imaging, Magellan's radar system was also used to collect altimetry data showing the elevations of various surface features. In this mode, pulses were sent directly downward and Magellan measured the time it took a radar pulse to reach Venus and return in order to determine the distance between the spacecraft and the planet.

Mission results

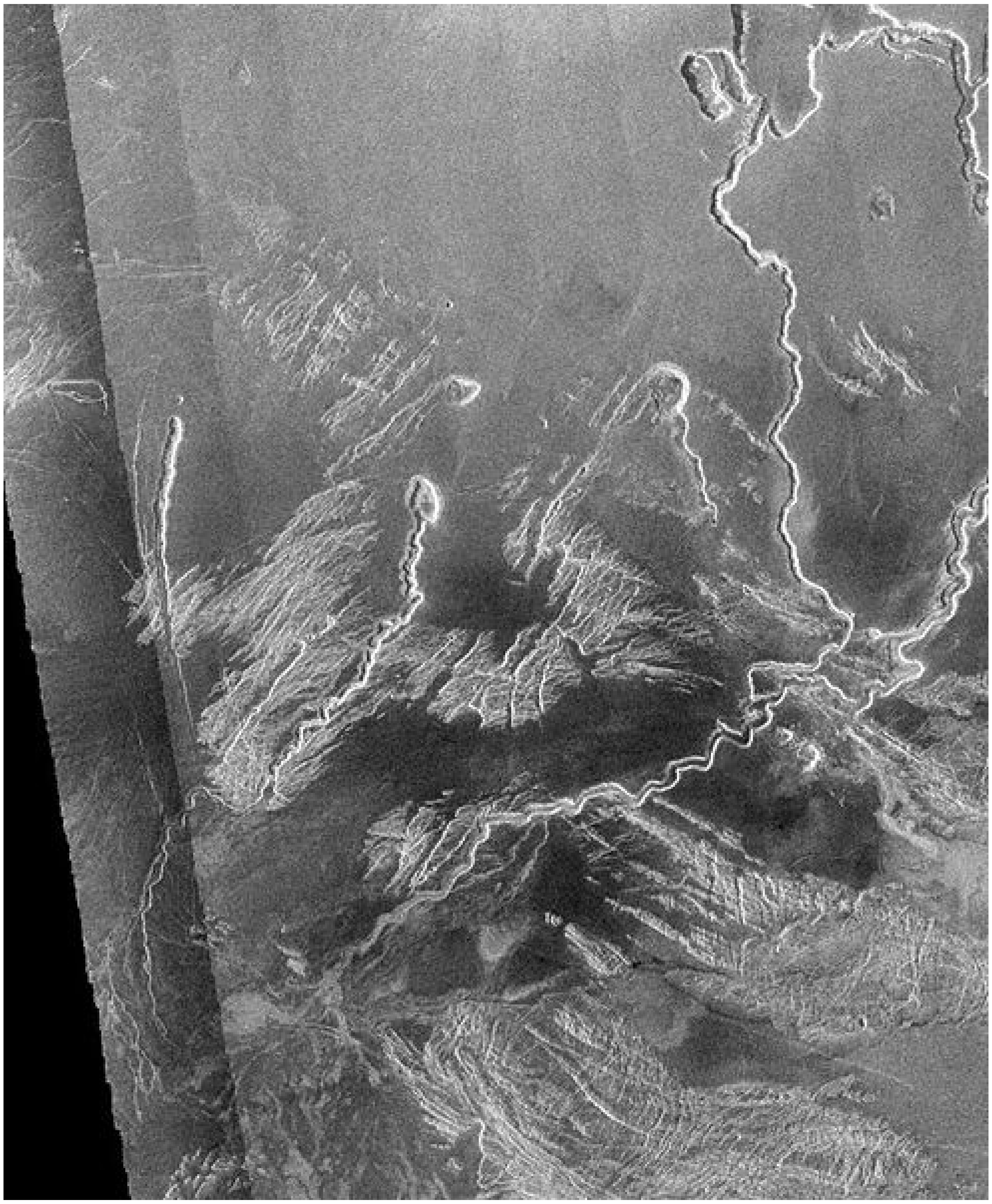


Image of the surface of Venus taken by the Magellan spacecraft.

Study of the Magellan high-resolution global images is providing evidence to better understand Venusian geology and the role of impacts, volcanism, and tectonism in the formation of Venusian surface structures. The surface of Venus is mostly covered by volcanic materials. Volcanic surface features, such as vast lava plains, fields of small lava domes, and large shield volcanoes are common. There are few impact craters on Venus, suggesting that the surface is, in general, geologically young - less than 800 million years old. The presence of lava channels over 6,000 kilometers long suggests river-like flows of extremely low-viscosity lava that probably erupted at a high rate. Large pancakeshaped volcanic domes suggest the presence of a type of lava produced by extensive evolution of crustal rocks.

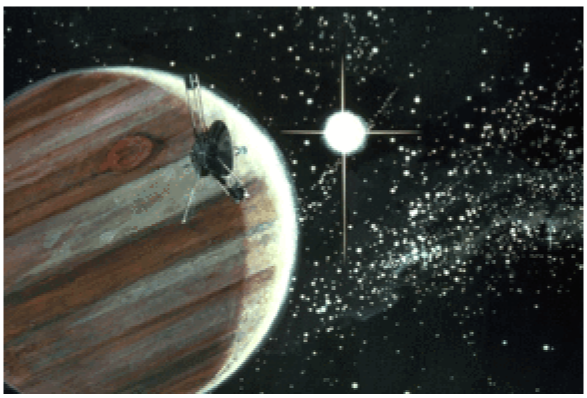
The typical signs of terrestrial plate tectonics - continental drift and basin floor spreading - are not in evidence on Venus. The planet's tectonics is dominated by a system of global rift zones and numerous broad, low domical structures called coronae, produced by the upwelling and subsidence of magma from the mantle.

Although Venus has a dense atmosphere, the surface reveals no evidence of substantial wind erosion, and only evidence of limited wind transport of dust and sand. This contrasts with Mars, where there is a thin atmosphere, but substantial evidence of wind erosion and transport of dust and sand.

Chapter- 2

Pioneer 10

Pioneer 10



An artist's concept of the Pioneer 10 Jupiter encounter

Operator	ARC / NASA
Major contractors	TRW
Mission type	Flyby
Flyby of	Jupiter
Launch date	1972-03-02 01:49:00 UTC (38 years, 11 months, and 15 days ago)
Launch vehicle	Atlas/Centaur/TE364-4
Launch site	Space Launch Complex 36A Cape Canaveral Air Force Station
Mission duration	Mar 2, 1972 - Jan 23, 2003 (30 years, 10 months, 22 days) (lost communication) Jupiter flyby

	(completed 1974-01-01) Interstellar mission *(completed 1997-03-31)*
COSPAR ID	1972-012A
Homepage	Pioneer Project website(archived) NASA Archive page
Mass	258 kg (569 lb)
Power	165.0 W (4 SNAP-19 RTGs)

Pioneer 10 (also known as *Pioneer F*) was a 258-kilogram robotic space probe launched by NASA on March 2, 1972 to study the asteroid belt, the environment around Jupiter, solar wind, cosmic rays, and eventually the far reaches of the solar system and heliosphere. It was the first spacecraft to traverse the asteroid belt and the first to encounter Jupiter. Due to power constraints and the vast distance of the probe, communication has been lost since January 23, 2003.

Mission background

History

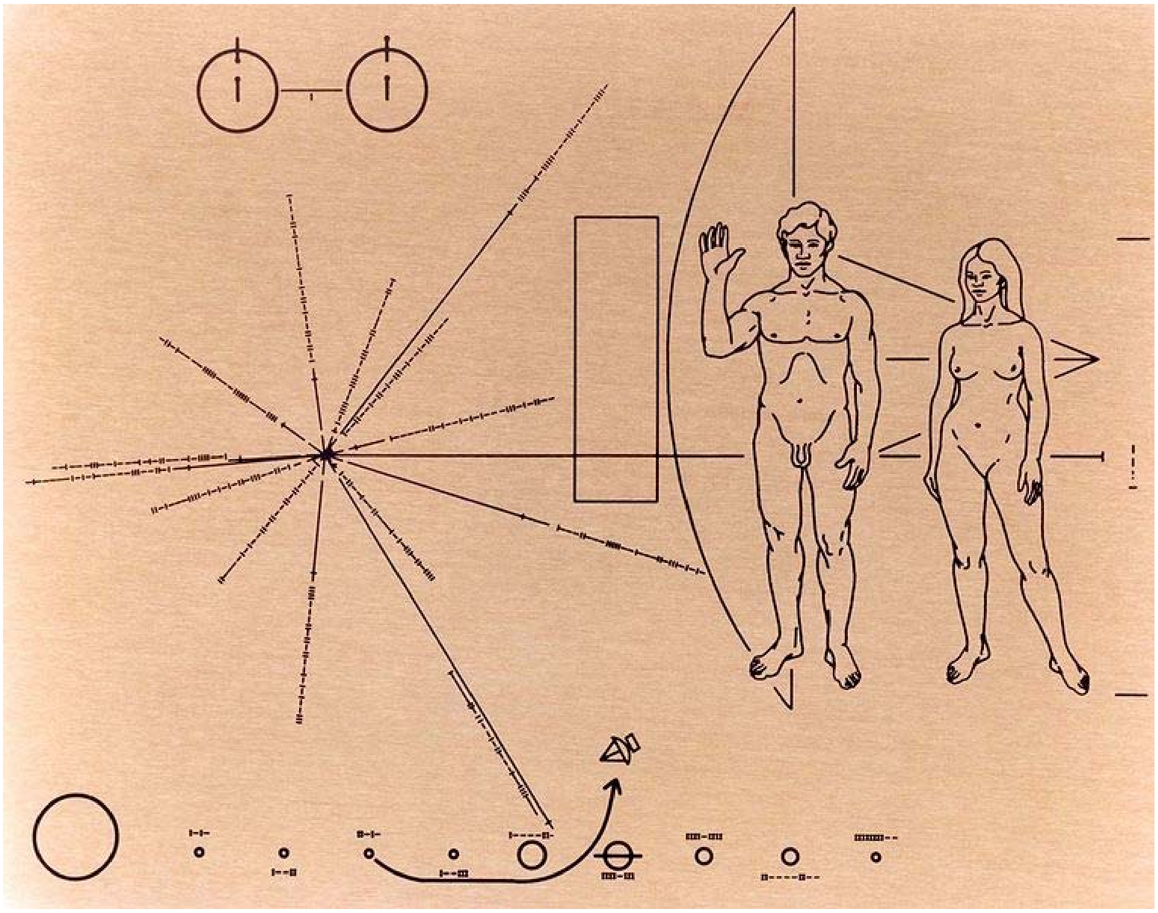
Approved in February 1969, *Pioneer 10* and twin probe *Pioneer 11*, were the first to be designed for exploring the outer solar system. Yielding to multiple proposals throughout the 1960s, early mission objectives were defined as:

- Explore the interplanetary medium beyond the orbit of Mars
- Investigate the nature of the asteroid belt from the scientific standpoint and assess the belt's possible hazard to missions to the outer planets.
- Explore the environment of Jupiter.

Later development-stage objectives also included the probe closely approaching Jupiter to provide data on the effect the environmental radiation surrounding Jupiter would have to the instruments on the spacecraft.

Pioneer 10 was built by TRW and managed as part of the Pioneer program by NASA Ames Research Center. A backup unit, Pioneer H, is currently on display in the "Milestones of Flight" exhibit at the National Air and Space Museum in Washington, D.C.. Many elements of the mission proved to be critical in the planning of the Voyager Program.

Pioneer plaque

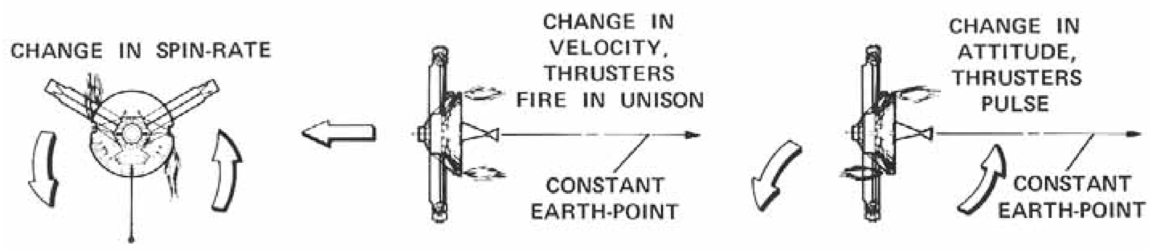


Pioneer 10 and Pioneer 11 carry a gold-anodized aluminium plaque in the event that either spacecraft is ever found by intelligent life-forms from other planetary systems. The plaques feature the nude figures of a human male and female along with several symbols that are designed to provide information about the origin of the spacecraft.

Spacecraft design

The *Pioneer 10* bus measures 36-centimeters deep and with six 76-centimeters long panels forming the hexagonal structure. The bus houses propellant to control the orientation of the probe and eight of the eleven scientific instruments. The spacecraft had a mass of 260-kilograms.

Attitude control and propulsion



Orientation of the spacecraft was maintained with six 4.5 N, hydrazine monopropellant thrusters: pair one maintained a constant spin-rate of 4.8-rpm, pair two controlled the forward thrust, pair three controlled attitude. Information for the orientation was provided by a star sensor able to reference Canopus, and two sun sensors.

Communications

The space probe included a redundant system of transceivers, one attached to the high-gain antenna, the other to an omni-antenna and medium-gain antenna. Each transceiver is 8 watts and transmits data across the S-band using 2110 MHz for the uplink from Earth and 2292 MHz for the downlink to Earth with the Deep Space Network tracking the signal. Prior to transmitting data, used a convolutional encoder, a form of error correction, to avoid sending corrupted data.

Power

Pioneer 10 used 4 SNAP-19 radioisotope thermoelectric generators (RTG) (***see diagram***). They were positioned on 2 three-rod trusses, each 3 meters (10 feet) in length and 120 degrees apart. This was expected to be a safe distance from the sensitive scientific experiments carried on board. Combined, the RTGs provided 155 watts at launch, and decayed to 140w in transit to Jupiter. The spacecraft required 100w to power all systems.

Computer

Much of the computation for the mission was performed on Earth and transmitted to the probe, where it was able to retain in memory, up to five commands of the

222 possible entries by ground controllers. The spacecraft included two command decoders and a command distribution unit, a very limited form of processor, to direct operations on the spacecraft. This system required that mission operators prepare commands long in advance of transmitting them to the probe. A data storage unit was included to record up to 6,144-bytes of information gathered by the instruments. The digital telemetry unit would then be used to prepare the collected data in one of the thirteen possible formats before transmitting it back to Earth.

Scientific instruments

Helium Vector Magnetometer (**HVM**)

Measures the fine structure of the interplanetary magnetic field, maps the Jovian magnetic field, and provides magnetic field measurements to evaluate solar wind interaction with Jupiter.

- **Principal investigator:** Edward Smith / JPL
- **Data:** PDS/PPI data catalog, NSSDC data archive

Quadrispherical Plasma Analyzer

Peers through a hole in the large dish-shaped antenna to detect particles of the solar wind originating from the Sun.

- **Principal investigator:** Aaron Barnes / NASA Ames Research Center (archived website)
- **Data:** PDS/PPI data catalog, NSSDC data archive

Charged Particle Instrument (**CPI**)

Detects cosmic rays in the Solar System.

- **Principal investigator:** John Simpson / University of Chicago
- **Data:** NSSDC data archive

Cosmic Ray Telescope (**CRT**)

Collects data on the composition of the cosmic ray particles and their energy ranges.

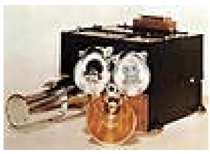
- **Principal investigator:** Frank McDonald / NASA Goddard Space Flight Center
- **Data:** PDS/PPI data catalog, NSSDC data archive

Geiger Tube Telescope (**GTT**)

Surveys the intensities, energy spectra, and angular distributions of electrons and protons along the spacecraft's path through the radiation belts of Jupiter. **Principal investigator:** James Van Allen / University of Iowa (website)

- **Data:** PDS/PPI data catalog, NSSDC data archive

Trapped Radiation Detector (**TRD**)



Includes an *unfocused Cerenkov counter* that detects the light emitted in a particular direction as particles pass through it recording electrons of energy, 0.5 to 12 MeV, an *electron scatter detector* for electrons of energy, 100 to 400 keV, and a *minimum ionizing detector* consisting of a solid-state diode that measures minimum ionizing particles (<3 MeV) and protons in the range of 50 to 350 MeV.
Principal investigator: R. Fillius / University of California San Diego

- **Data:** NSSDC data archive

Meteoroid Detectors

Twelve panels of pressurized cell detectors mounted on the back of the main dish antenna record penetrating impacts of small meteoroids.

- **Principal investigator:** William Kinard / NASA Langley Research Center
- **Data:** NSSDC data archive list

Asteroid/Meteoroid Detector (**AMD**)

Meteoroid-asteroid detector looks into space with four non-imaging telescopes to track particles ranging from close-by bits of dust to distant large asteroids.

- **Principal investigator:** Robert Soberman / General Electric Company
- **Data:** NSSDC data archive

Ultraviolet Photometer

Ultraviolet light is sensed to determine the quantities of hydrogen and helium in space and on Jupiter.

- **Principal investigator:** Darrell Judge / University of Southern California
- **Data:** PDS/PPI data catalog, NSSDC data archive

Imaging Photopolarimeter (**IPP**)

The imaging experiment relies upon the spin of the spacecraft to sweep a small telescope across the planet in narrow strips only 0.03 degrees wide, looking at the planet in red and blue light. These strips were then processed to build up a visual image of the planet.

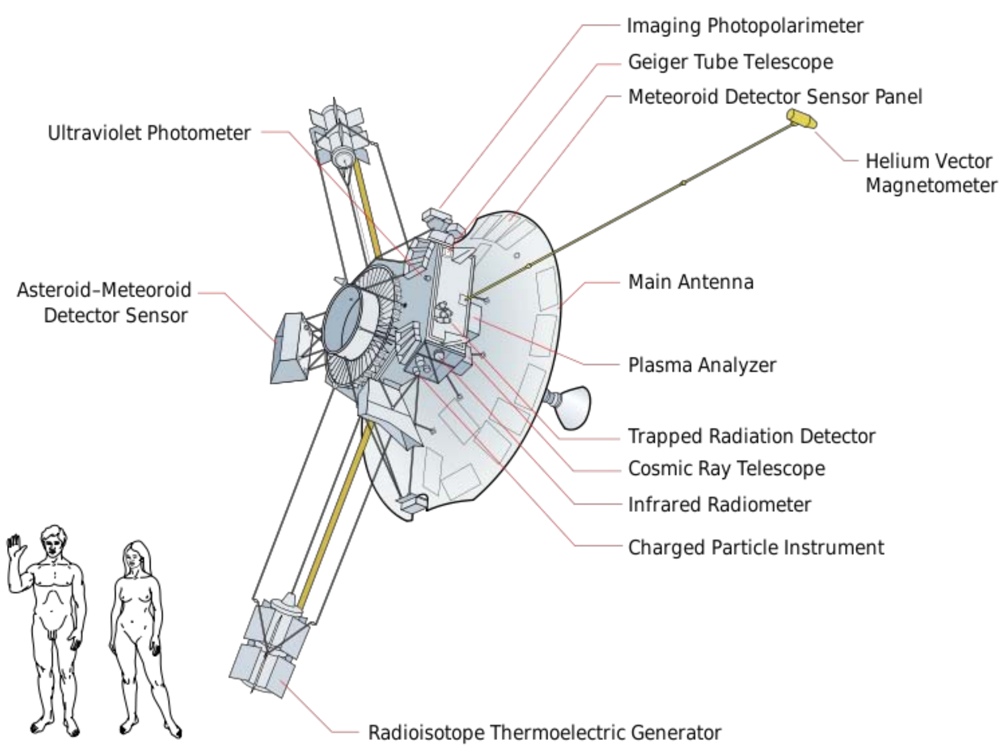
- **Principal investigator:** Tom Gehrels / University of Arizona
- **Data:** NSSDC data archive list

Infrared Radiometer

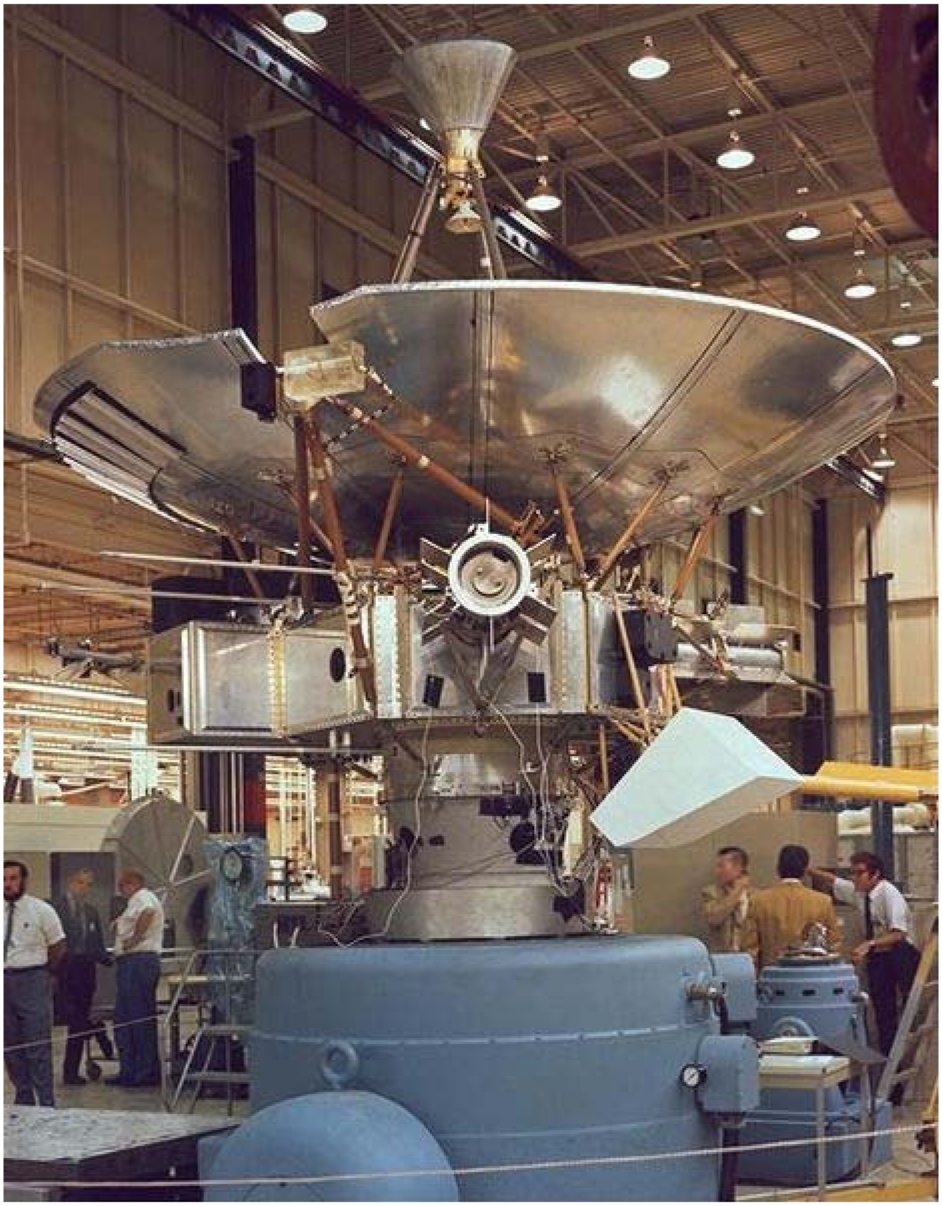
Provides information on cloud temperature and the output of heat from Jupiter.

- **Principal investigator:** Andrew Ingersoll / California Institute of Technology

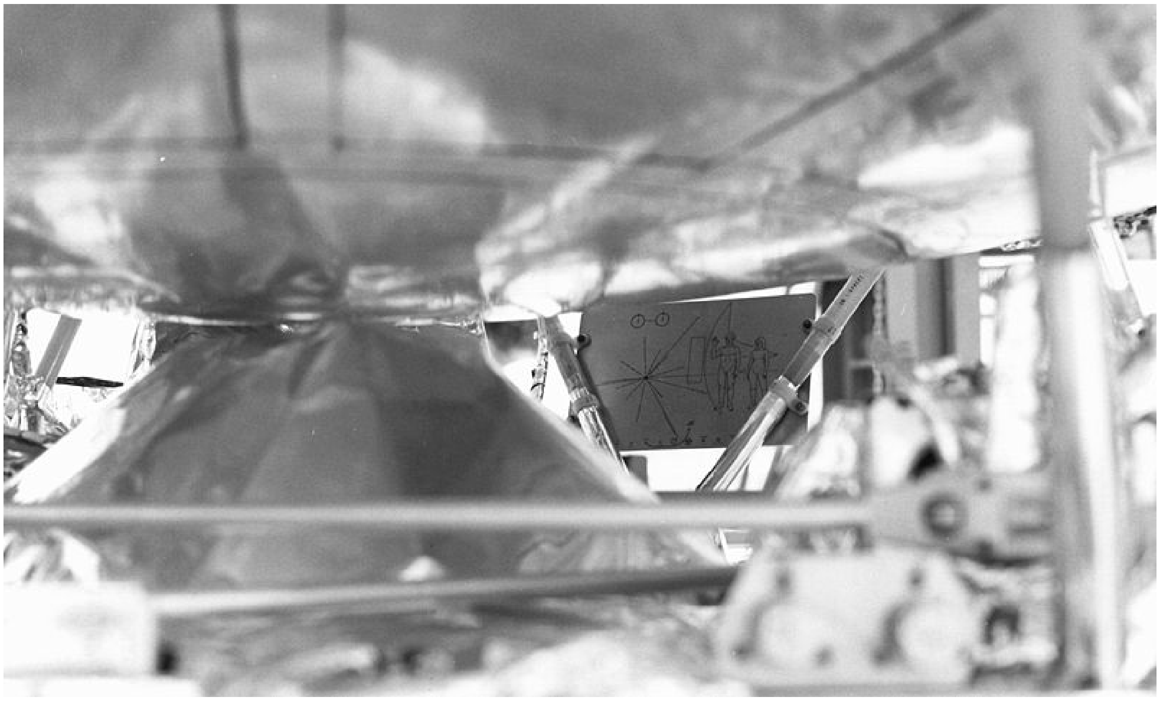
Images of the spacecraft



Pioneer 10 and Pioneer 11 spacecraft diagram.



Pioneer 10 in the final stages of construction.



The Pioneer plaque fixed to the space probe.

Pioneer 10 on a kick motor just prior to be encapsulated for launch.

Mission profile

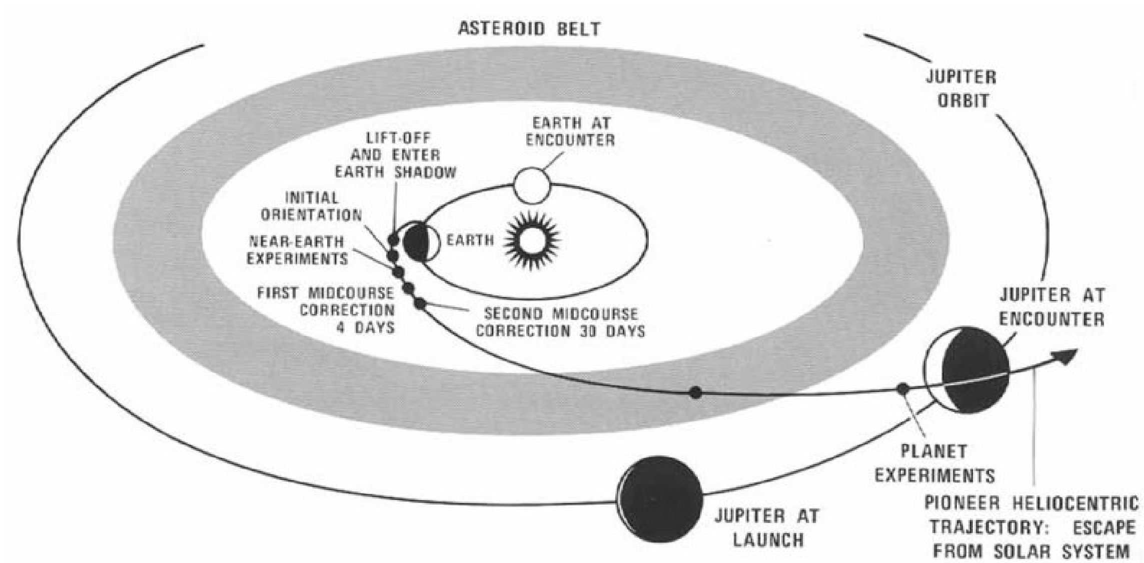
Timeline of travel

Date	Event
1972-03-03	Spacecraft launched
1972-06-	Crossed orbit of Mars.
1972-07-15	Entered the asteroid belt.
1972-07-15	Start Jupiter observation phase. **Time** **Event**
1974-01-01	Begin Pioneer Interstellar Mission.

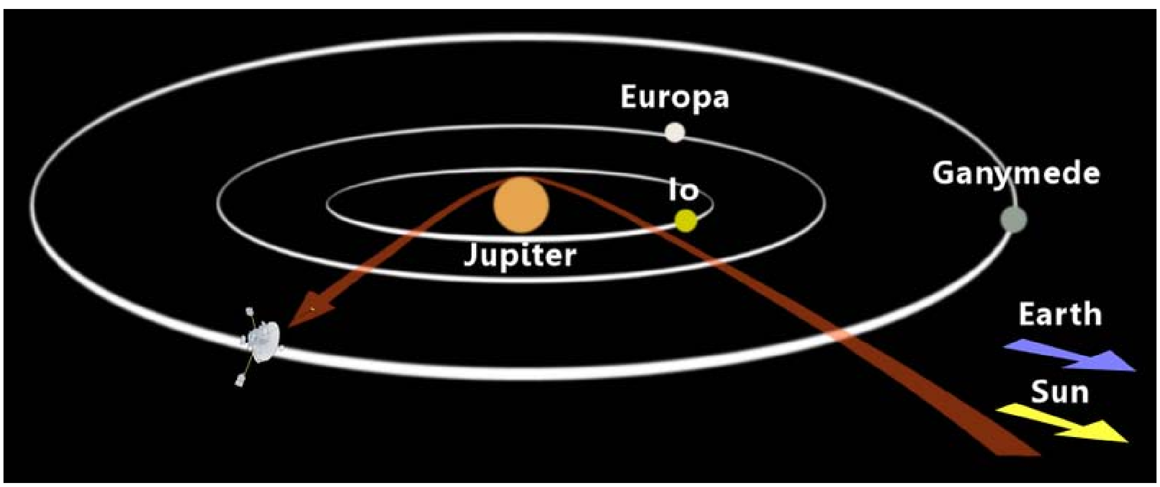
Launch and trajectory

The *Pioneer 10* probe was launched on March 3, 1972 at 01:49:00 UTC by the National Aeronautics and Space Administration from Space Launch Complex 36A at Cape Canaveral, Florida aboard an Atlas/Centaur launch vehicle. The launch vehicle accelerated the probe for 17 minutes, reaching a velocity of 51,682 kilometers/hour (32,114 miles/hour) passing by the moon in 11 hours and becoming the fastest man-made object at that time. Twin probe, Pioneer 11, would launch a year later on April 4, 1973.

Pioneer 10 launching from Space Launch Complex 36A



Pioneer 10 interplanetary trajectory



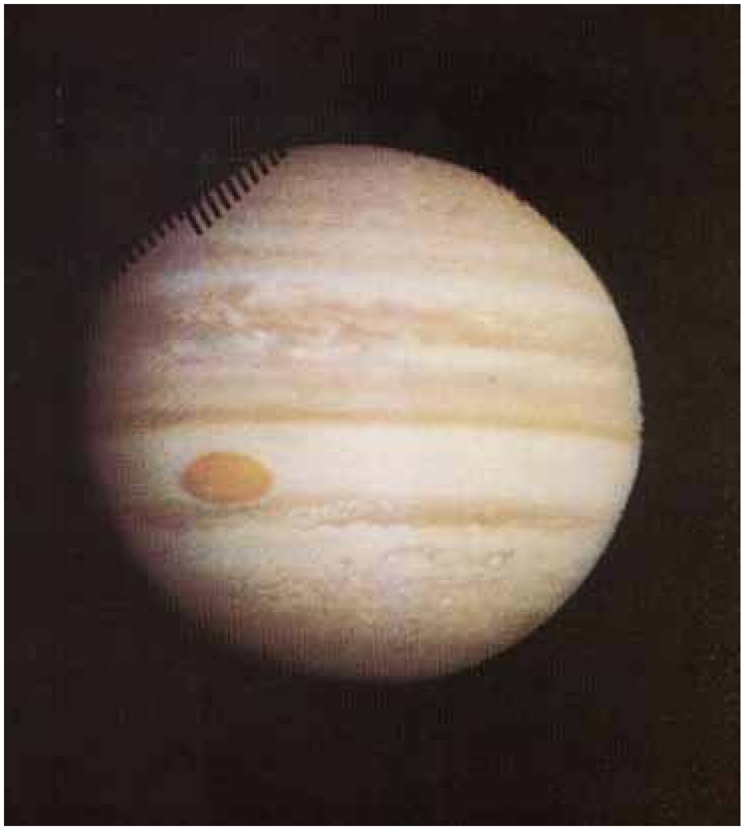
Pioneer 10 trajectory through the Jovian system

Encounter with Jupiter

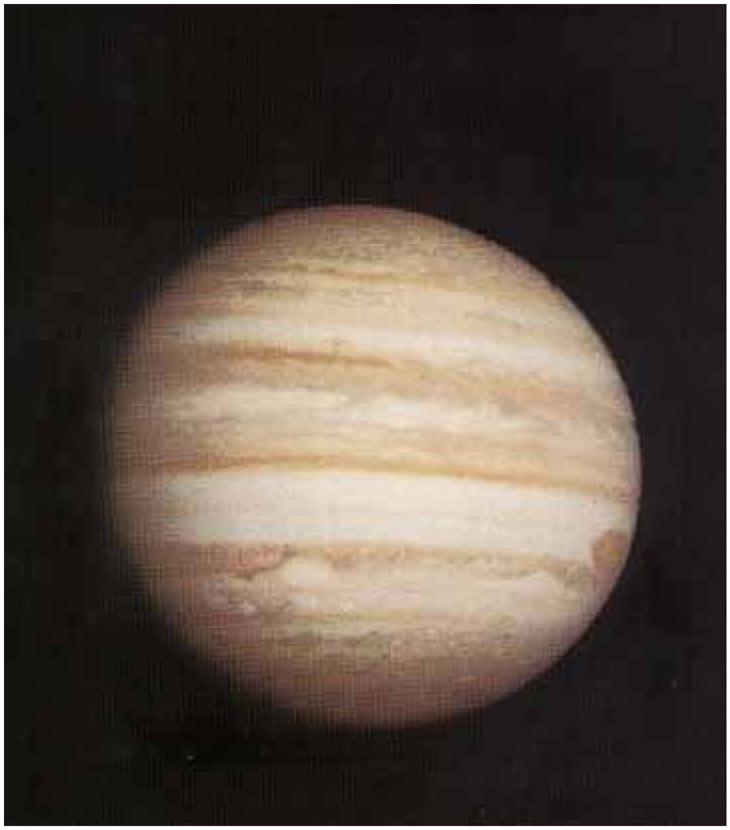
In November and December 1973, *Pioneer 10* began transmitting images of Jupiter back to Earth. 500 images of Jupiter had been received by December 2, 1973, revealing little detail. However, within the 48 hours prior to closest approach, the probe exceeded the resolution of Earth based observations, revealing many previously unseen details.

On December 4, 1973, *Pioneer 10* reached closest approach to Jupiter, passing 200,000 kilometers (124,274 miles) above the cloud tops.

Jupiter encounter (frame 1)



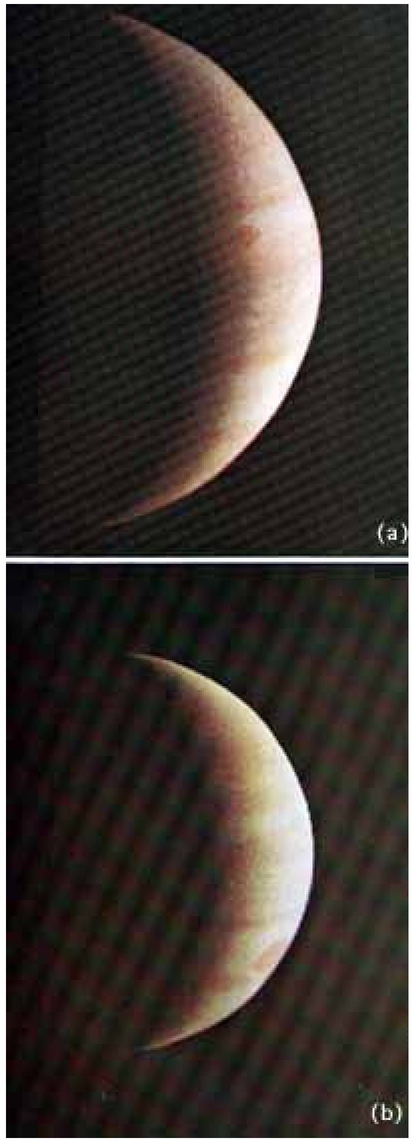
Jupiter encounter (frame 2)



Jupiter encounter (frame 3)

Jupiter encounter (frame 4)

Highest detailed image of the *Pioneer 10* encounter of Jupiter.



Sunrise on a crescent-shaped Jupiter.

Ganymede as seen from *Pioneer 10*.

Europa as seen by Pioneer 10

Interstellar mission

Pioneer anomaly

Analysis of the radio tracking data from the *Pioneer 10* and *11* spacecraft at distances between 20–70 AU from the Sun has consistently indicated the presence of a small but anomalous Doppler frequency drift. The drift can be interpreted as due to a constant acceleration of $(8.74 \pm 1.33) \times 10^{-10}$ m/s^2 directed towards the Sun. Although it is suspected that there is a systematic origin to the effect, none has been found. As a result, there is growing interest in the nature of this anomaly.

Current status

An artist's depiction of Pioneer 10 in the outer solar system

After March 31, 1997, *Pioneer 10*'s weak signal continued to be tracked by the Deep Space Network to aid the training of flight controllers in the process of acquiring deep space radio signals. There was an Advanced Concepts study applying chaos theory to extract coherent data from the fading signal.

On **April 27, 2002**, the last successful reception of telemetry was received from *Pioneer 10*; subsequent signals were barely strong enough to detect and provided no usable data.

On **January 23, 2003**, the last, very weak signal from *Pioneer 10* was received when it was 12 billion-kilometers (80 AU) from Earth. Further attempts to contact the spacecraft were unsuccessful. The final attempt was made on the evening of March 4, 2006, the last time the antenna would be correctly aligned with Earth. No response was received from *Pioneer 10*. Loss of contact was probably due to a combination of increasing distance and the steadily weakening power source on the spacecraft.

Pioneer 10 is heading in the direction of the star Aldebaran in the constellation Taurus at approximately 2.6 AU per year. If Aldebaran had zero relative velocity, it would take *Pioneer 10* approximately 2 million years to reach the star.

Chapter- 3

Voyager 1

Voyager 1

Voyager spacecraft

Operator	NASA / JPL
Mission type	Flyby
Flyby of	Jupiter, Saturn
Launch date	1977-09-05 12:56:00 UTC (33 years, 5 months, and 13 days ago)
Launch vehicle	Titan IIIE / Centaur
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In progress (Interstellar mission) (32 years, 1 month, and 14 days elapsed) Jupiter encounter

	(completed 1979-04-13)
	Saturn encounter
	(completed 1980-12-14)
COSPAR ID	1977-084A
Homepage	NASA *Voyager* website
Mass	721.9 kg (1,592 lb)
Power	420 W (3 RTGs)

The ***Voyager 1*** spacecraft is a 722-kilogram (1,592 lb) robotic American space probe launched by NASA on September 5, 1977 to study the outer Solar System and eventually interstellar space. Operating for 33 years, 5 months, and 13 days, the spacecraft receives routine commands and transmits data back to the Deep Space Network. It was the first probe to leave the Solar System and is the farthest human-made object from Earth.

Currently in extended mission, the spacecraft is tasked with locating and studying the boundaries of the Solar System, including the Kuiper belt, the heliosphere and interstellar space. The primary mission ended November 20, 1980, after encountering the Jovian system in 1979 and the Saturnian system in 1980. It was the first probe to provide detailed images of the two largest planets and their moons.

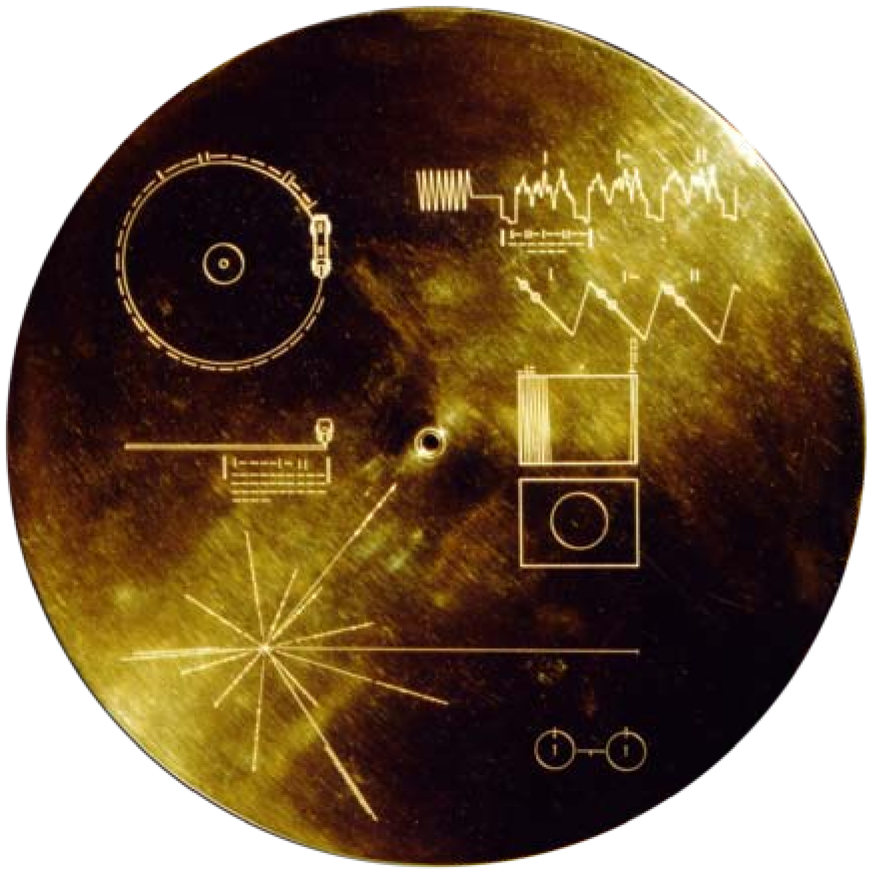
Mission background

History

Conceived in the 1960s, a Grand Tour proposal to study the outer planets, prompted NASA to begin work on a mission in the early 1970s. The development of the interplanetary probes coincided with an alignment of the planets, making possible a mission to the outer Solar System by taking advantage of the then-new technique, gravity assist.

Utilizing gravity assists would enable a single probe to visit the four gas giants (Jupiter, Saturn, Uranus, and Neptune) while requiring a minimal amount of propellant and a shorter transit duration between planets. Originally, *Voyager 1* was planned as *Mariner 11* of the Mariner program however, due to congressional budget cuts, the mission was scaled back to be a flyby of Jupiter and Saturn, and renamed the Mariner Jupiter-Saturn probes. As the program progressed, the name was later changed to Voyager as the probe designs began to differ greatly from previous Mariner missions.

Golden record



Each *Voyager* space probe carries a gold-plated audio-visual disc in the event that either spacecraft is ever found by intelligent life-forms from other planetary systems. The discs carry photos of the Earth and its lifeforms, a range of scientific information, spoken greetings from the people (e.g. the Secretary-General of the United Nations and the President of the United States, and the children of the Planet Earth) and a medley, "Sounds of Earth", that includes the sounds of whales, a baby crying, waves breaking on a shore, and a variety of music.

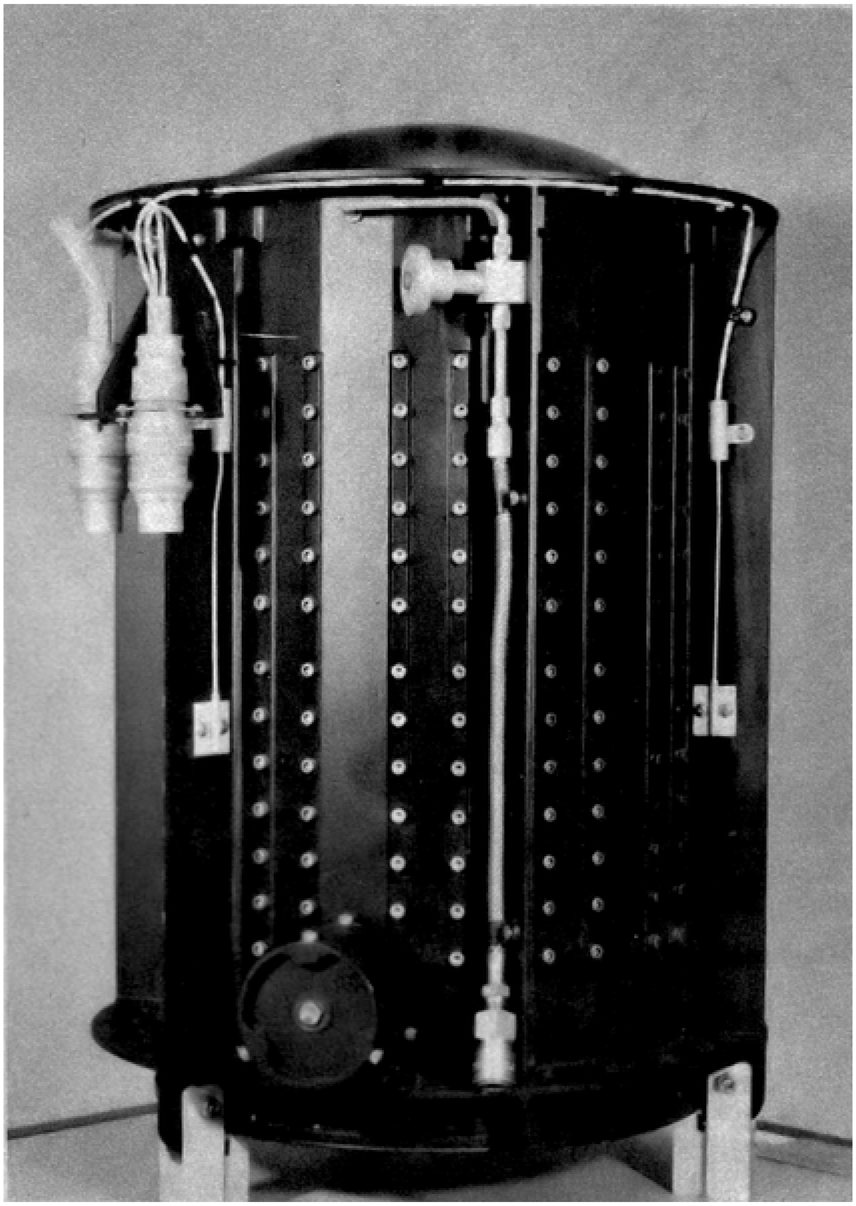
Spacecraft design

Constructed by the Jet Propulsion Laboratory, *Voyager 1* included 16 hydrazine thrusters, three-axis stabilization, gyroscopes and celestial referencing instruments (sun sensor/Canopus Star Tracker) to maintain pointing of the high-gain antenna toward Earth. Collectively these instruments are part of the Attitude and Articulation Control Subsystem (**AACS**) along with redundant units of most instruments and 8 backup thrusters. The spacecraft also included 11 scientific instruments to study celestial objects as it traveled through space.

Communications

Built with the intent for eventual interstellar travel, *Voyager 1* included a large, 3.7-meter parabolic, high-gain antenna (***see diagram***) to transceive data with the Deep Space Network on Earth. Communications are conducted over the S-band (13 cm wavelength) and X-band (3.6 cm wavelength) providing bandwidth as high as 115.2 kilobits per second. When the spacecraft is unable to communicate with Earth, the Digital Tape Recorder (**DTR**) is able to record up to 62,500-kilobytes of data to later transmit when communication is reestablished.

Power



The spacecraft was built with 3 Multihundred-Watt radioisotope thermoelectric generators (**MHW RTG**). Each RTG includes 24 pressed plutonium oxide spheres and provide enough heat to generate approximately 157 Watts of power at launch. Collectively, the RTGs supply the spacecraft with 470 Watts at launch and will allow operations to continue until at least 2025. (***see diagram 1***, ***2***)

Scientific instruments

Expand

Instrument Name	Abr.	Description	
Imaging Science System	**(ISS)**	Utilizes a two-camera system (narrow-angle/wide-angle) to provide imagery of Jupiter, Saturn and other objects along the trajectory.	**Wide Angle Camera Filters**

Name	Wavelength	Spectrum	Sensitivity

Narrow Angle Camera Filters

Name	Wavelength	Spectrum	Sensitivity
Clear	280 nm - 640 nm		
UV	280 nm - 370 nm		
Violet	350 nm - 450 nm		
Blue	430 nm - 530 nm		
'	'		'
Green	530 nm - 640 nm		
'	'		'
Orange	590 nm - 640 nm		
'	'		'

Clear	280 nm - 640 nm		
'	'	'	
Violet	350 nm - 450 nm		
Blue	430 nm - 530 nm		
CH_4-U	536 nm - 546 nm		
Green	530 nm - 640 nm		
Na-D	588 nm - 590 nm		
Orange	590 nm - 640 nm		
CH_4-JST	614 nm - 624 nm		

- **Principal investigator:** Bradford Smith / University of Arizona (PDS/PRN website)
- **Data:** PDS/PDI data catalog, PDS/PRN data catalog

Radio Science System **(disabled)** **(RSS)**

Utilized the telecommunications system of the Voyager spacecraft to determine the physical properties of planets and satellites (ionospheres, atmospheres, masses, gravity fields, densities) and the amount and size distribution of material in Saturn's rings and the ring dimensions.

- **Principal investigator:** G. Tyler / Stanford University PDS/PRN overview
- **Data:** PDS/PPI data catalog, PDS/PRN data catalog **(**VG_2803**)**, NSSDC data archive

Infrared Interferometer Spectrometer **(disabled)** **(IRIS)**

Investigates both global and local energy balance and atmospheric composition. Vertical temperature profiles are also obtained from the planets and satellites as well as the composition, thermal properties, and size of particles in Saturn's rings.

- **Principal investigator:** Rudolf Hanel / NASA Goddard Space Flight Center (PDS/PRN website)
- **Data:** PDS/PRN data catalog, PDS/PRN expanded data catalog **(**VGIRIS_0001, VGIRIS_002**)**, NSSDC Jupiter data archive

Ultraviolet Spectrometer **(active)** **(UVS)**

Designed to measure atmospheric properties, and to measure radiation.

- **Principal investigator:** A. Broadfoot / University of Southern California (PDS/PRN website)
- **Data:** PDS/PRN data catalog

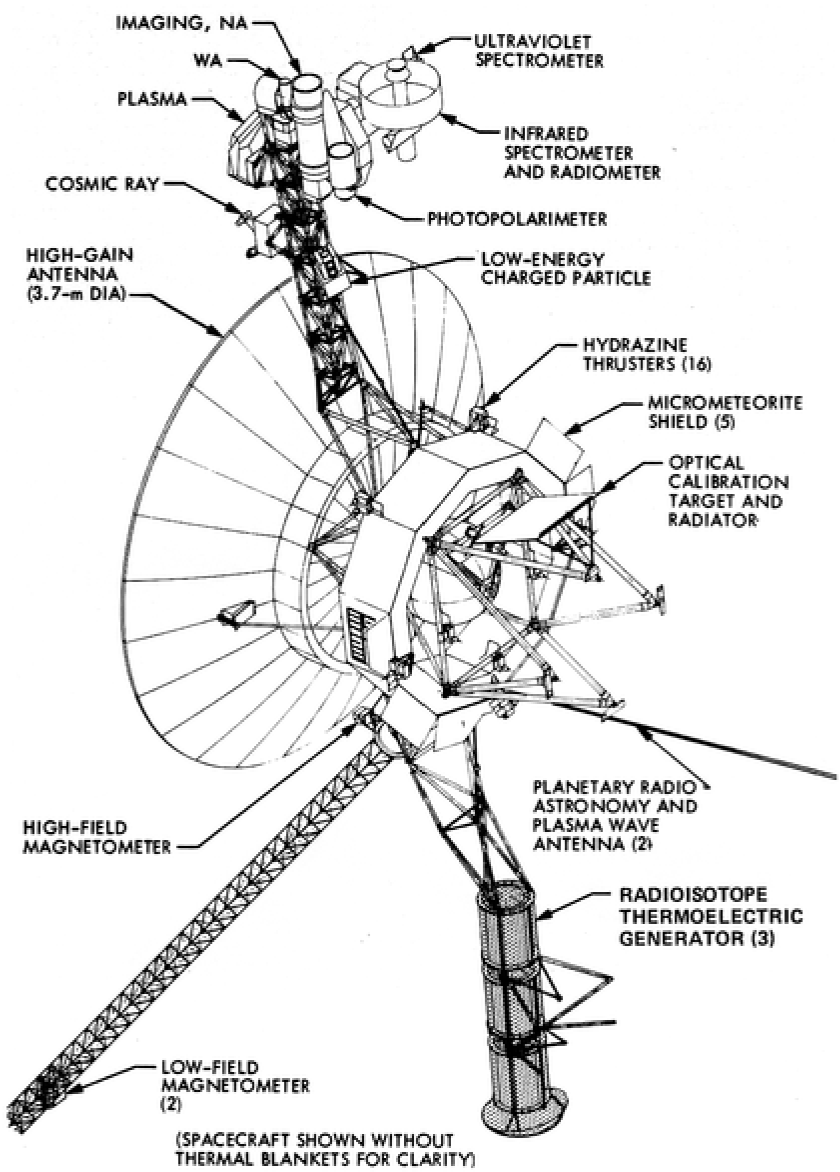
Triaxial Fluxgate Magnetometer **(active)** **(MAG)**

Designed to investigate the magnetic fields of Jupiter and Saturn, the solar-wind interaction with the magnetospheres of these planets, and the interplanetary magnetic field out to the solar wind boundary with the interstellar magnetic field and beyond, if crossed.

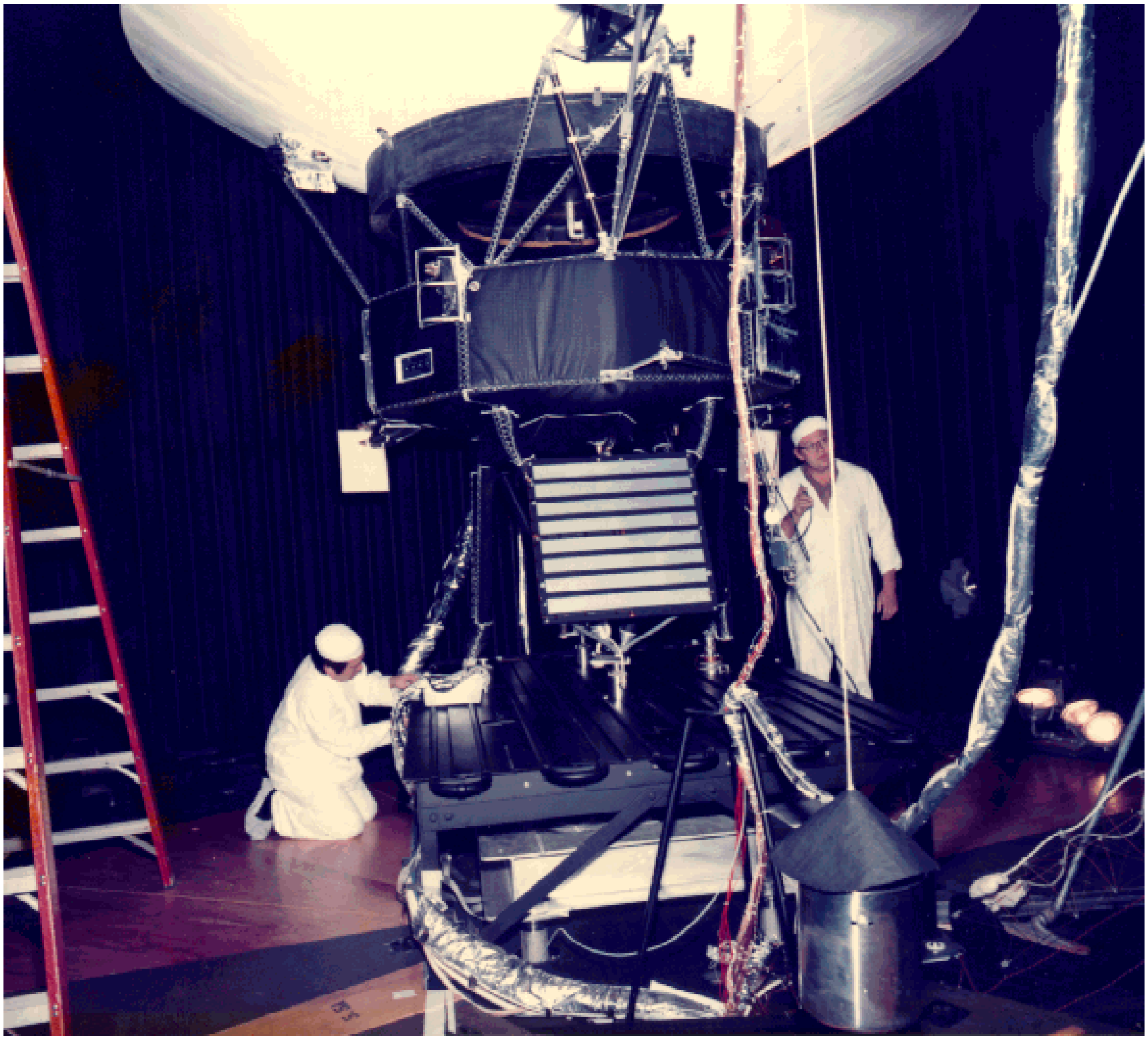
- **Principal investigator:** Norman Ness / NASA Goddard Space Flight Center (website)
- **Data:** PDS/PPI data catalog, NSSDC data archive

Plasma Spectrometer (**defective**)	(**PLS**)	Investigates the macroscopic properties of the plasma ions and measures electrons in the energy range from 5 eV to 1 keV. • **Principal investigator:** John Richardson / MIT (website) • **Data:** PDS/PPI data catalog, NSSDC data archive
Low Energy Charged Particle Instrument (**active**)	(**LECP**)	Measures the differential in energy fluxes and angular distributions of ions, electrons and the differential in energy ion composition. • **Principal investigator:** Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website) • **Data:** UMD data plotting, PDS/PPI data catalog, NSSDC data archive
Cosmic Ray System (**active**)	(**CRS**)	Determines the origin and acceleration process, life history, and dynamic contribution of interstellar cosmic rays, the nucleosynthesis of elements in cosmic-ray sources, the behavior of cosmic rays in the interplanetary medium, and the trapped planetary energetic-particle environment. • **Principal investigator:** Edward Stone / CalTech / NASA Goddard Space Flight Center (website) • **Data:** PDS/PPI data catalog, NSSDC data archive
Planetary Radio Astronomy Investigation (**disabled**)	(**PRA**)	Utilizes a sweep-frequency radio receiver to study the radio-emission signals from Jupiter and Saturn. • **Principal investigator:** James Warwick / University of Colorado • **Data:** PDS/PPI data catalog, NSSDC data archive
Photopolarimeter System (**defective**)	(**PPS**)	Utilized a telescope with a polarizer to gather information on surface texture and composition of Jupiter and Saturn and information on atmospheric scattering properties and density for both planets. • **Principal investigator:** Arthur Lane / JPL (PDS/PRN website) • **Data:** PDS/PRN data catalog
Plasma Wave System (**partially disabled**)	(**PWS**)	Provides continuous, sheath-independent measurements of the electron-density profiles at Jupiter and Saturn as well as basic information on local wave-particle interaction, useful in studying the magnetospheres. • **Principal investigator:** Donald Gurnett / University of Iowa (website) • **Data:** PDS/PPI data catalog, NSSDC data archive

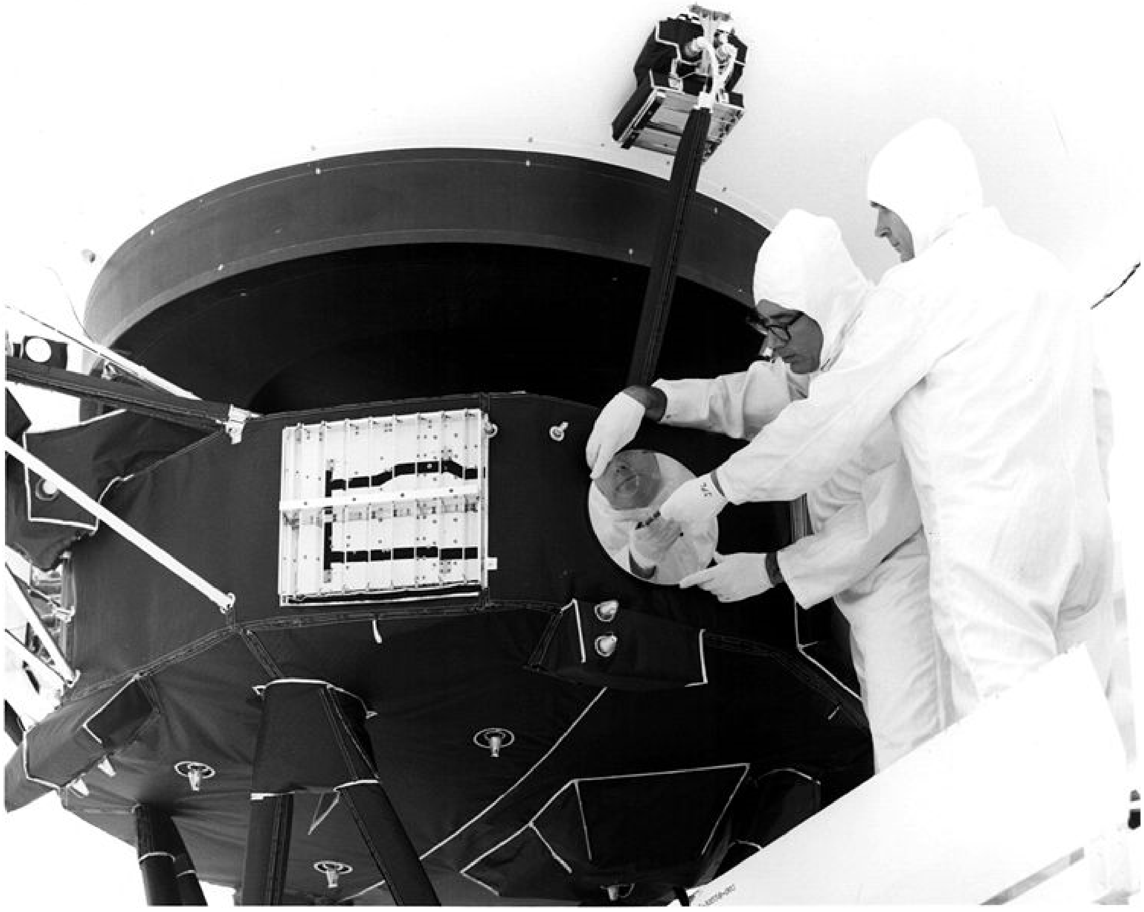
Images of the spacecraft



Voyager spacecraft diagram.



Voyager 1 in a space simulator chamber.



Gold-Plated Record is attached to *Voyager 1*.

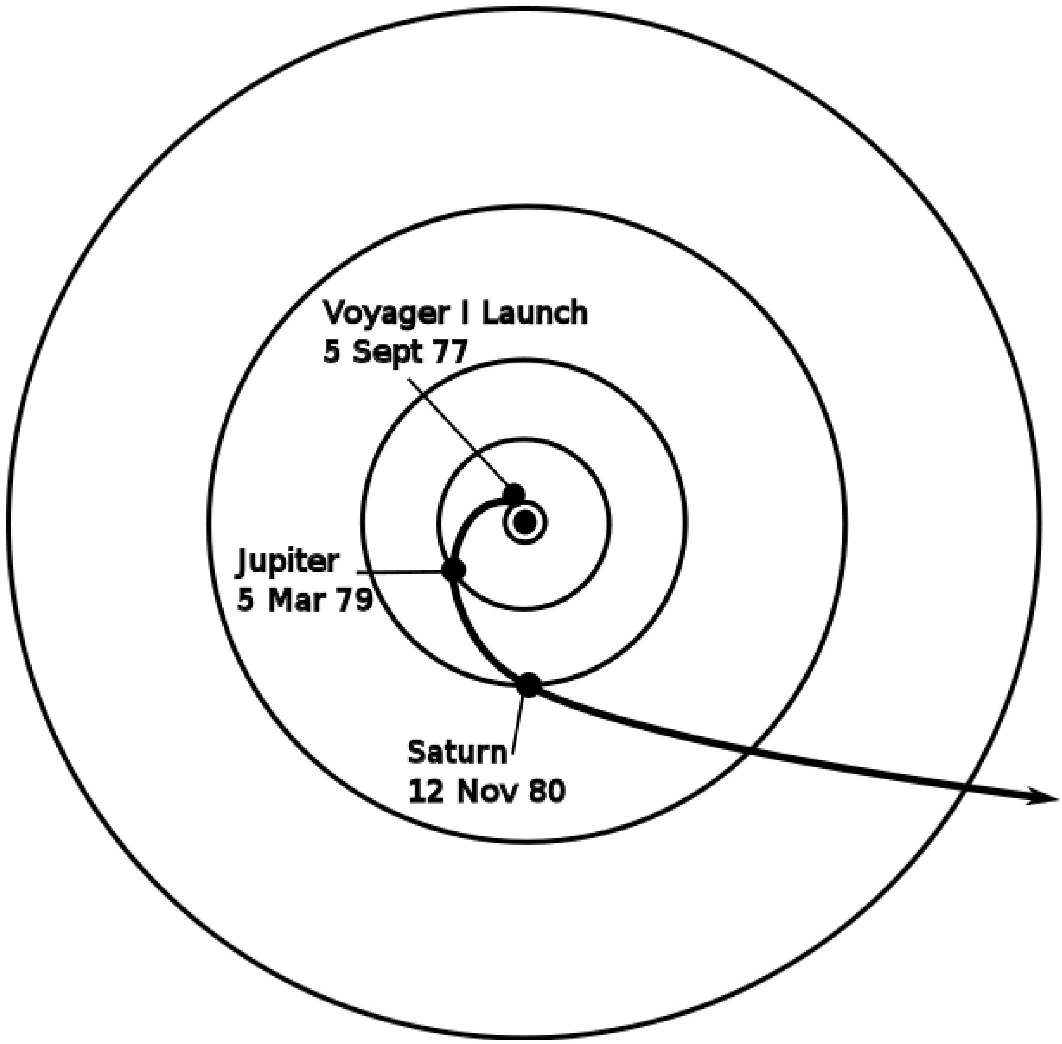
Voyager 1 awaiting payload entry into a Titan/Centaur-6 rocket.

Mission profile

Launch and trajectory

The *Voyager 1* probe was launched on September 5, 1977, by the National Aeronautics and Space Administration from Space Launch Complex 41 at Cape Canaveral, Florida, aboard a Titan IIIE/Centaur launch vehicle. Two weeks prior, the twin *Voyager 2* probe had been launched on August 20, 1977. Despite being launched two weeks later, *Voyager 1* reached both Jupiter and Saturn sooner after being launched into a shorter trajectory.

Voyager 1 lifted off with a Titan IIIE/Centaur

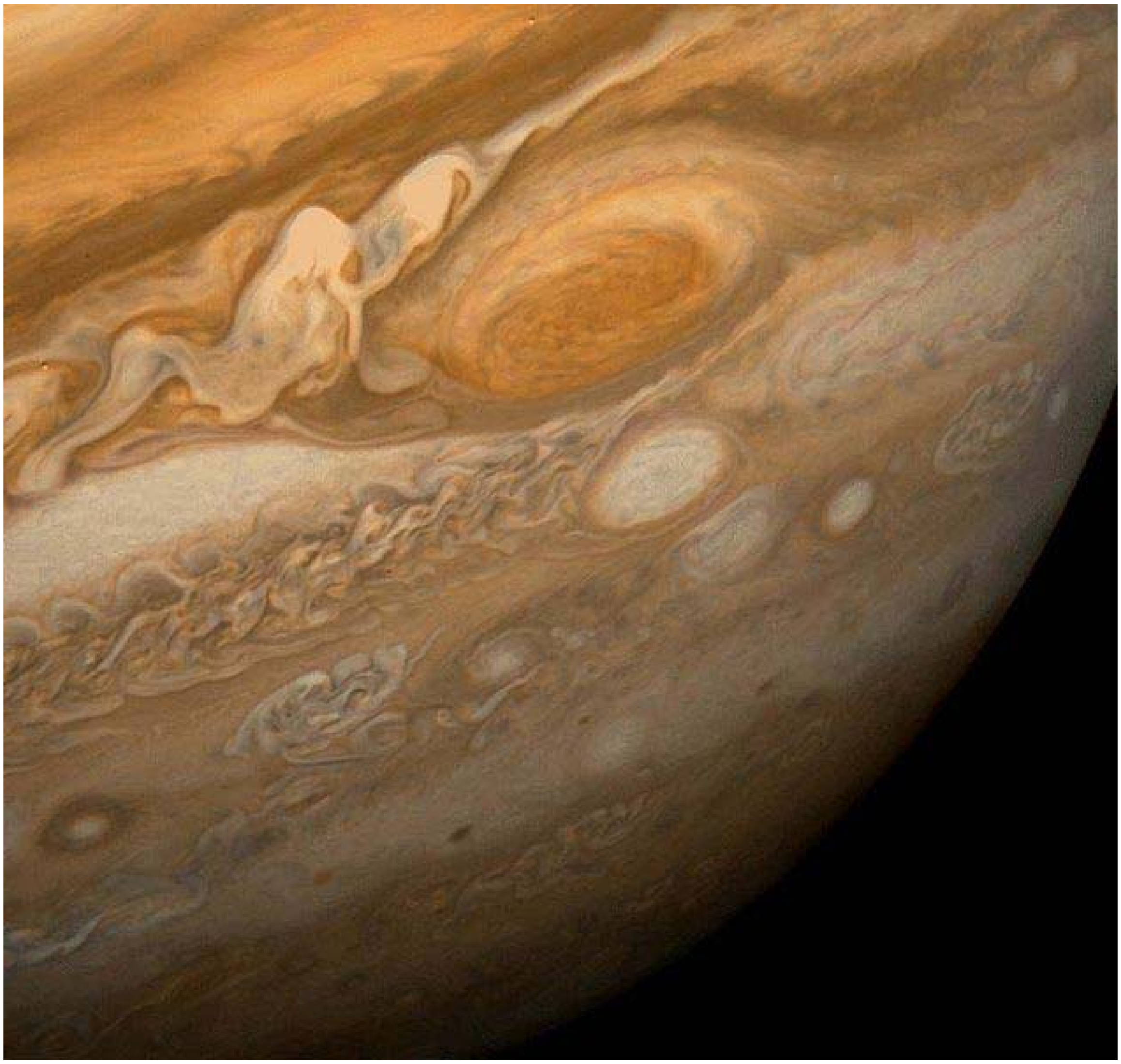


Trajectory of *Voyager 1* primary mission.

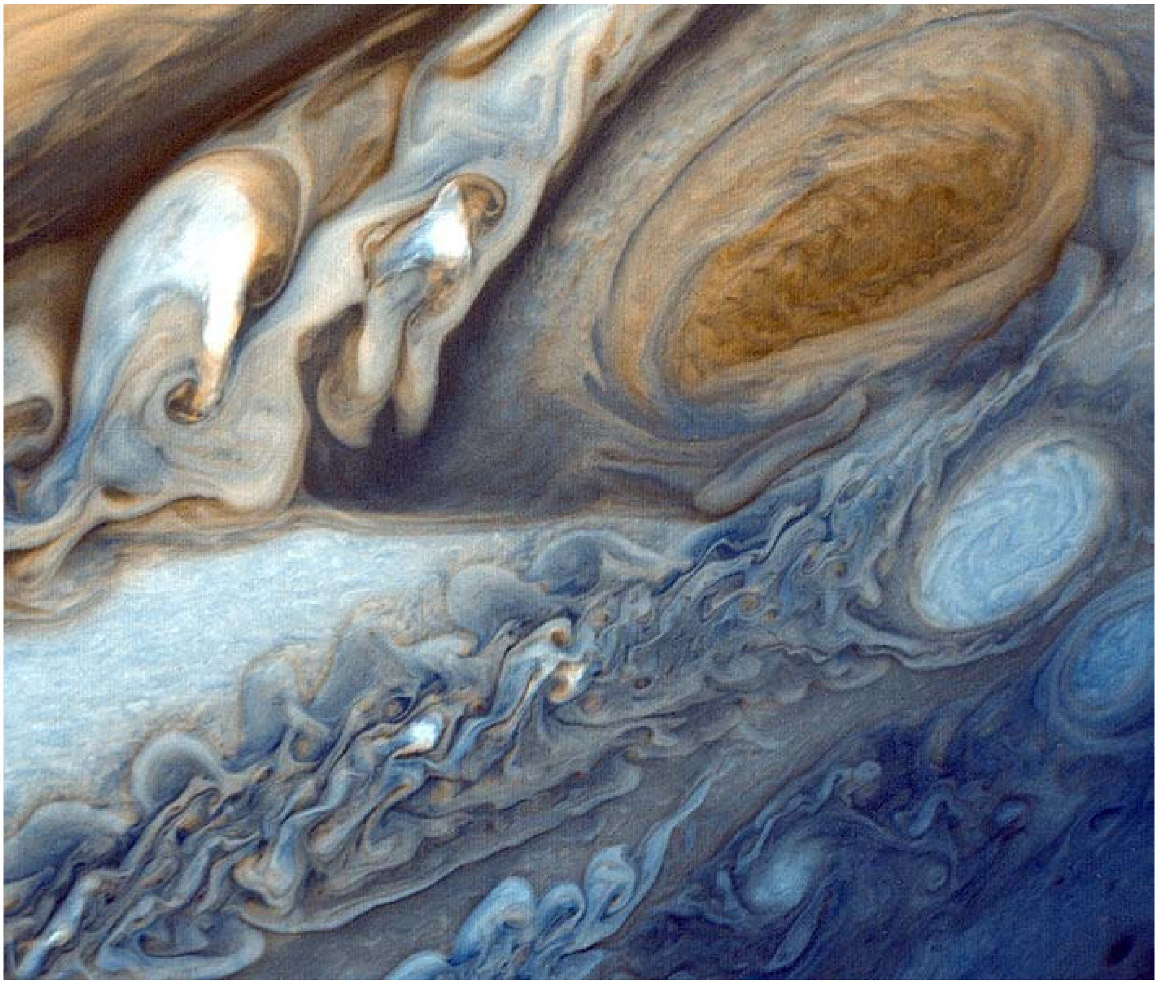
Encounter with Jupiter

Voyager 1 began photographing Jupiter in January 1979. Its closest approach to Jupiter was on March 5, 1979, at a distance of about 349,000 kilometres (217,000 miles) from the planet's center. Due to the greater photographic resolution allowed by a closer approach, most observations of the moons, rings, magnetic fields, and the radiation belt environment of the Jovian system were made during the 48-hour period that bracketed the closest approach. Voyager 1 finished photographing the Jovian system in April 1979.

The two *Voyager* space probes made a number of important discoveries about Jupiter, its satellites, its radiation belts, and its never-before-seen planetary rings. The most surprising discovery in the Jovian system was the existence of volcanic activity on the moon Io, which had not been observed either from the ground, or by *Pioneer 10* or *11*.

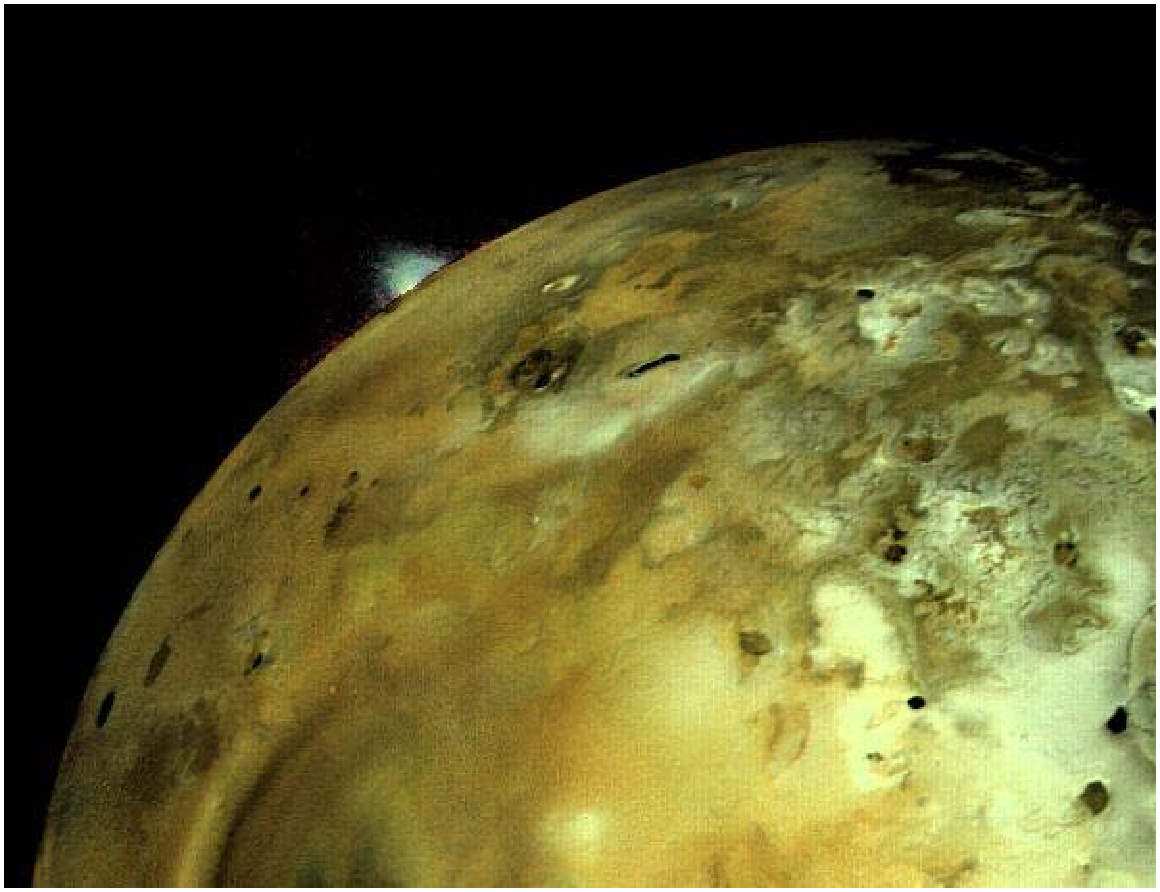


The Great Red Spot as seen from *Voyager 1*.



False color detail of Jupiter's atmosphere.

View of lava flows radiating from the volcano Ra Patera on Io.



Volcanic eruption on Io photographed from *Voyager 1*.

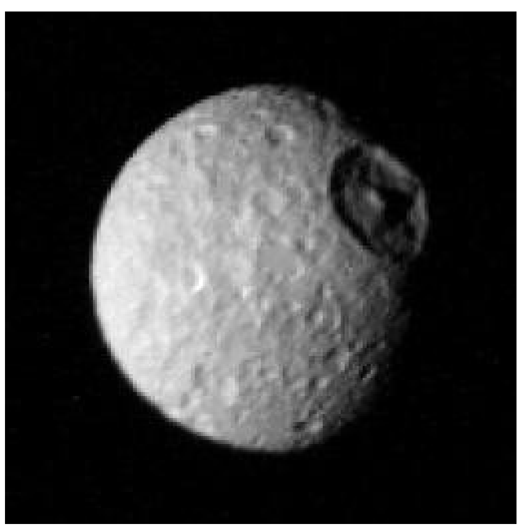
Encounter with Saturn

The gravitational assist trajectories at Jupiter were successfully carried out by both *Voyagers*, and the two spacecraft went on to visit Saturn and its system of moons and rings. *Voyager 1*'s Saturnian flyby occurred in November 1980, with the closest approach on November 12, 1980, when the space probe came within 124,000 kilometers (77,000 mi) of Saturn's cloud-tops. The space probe's cameras detected complex structures in the rings of Saturn, and its remote sensing instruments studied the atmospheres of Saturn and its giant moon Titan.

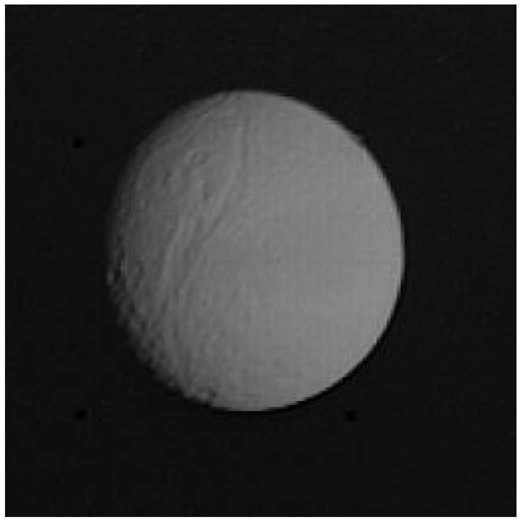
Because Pioneer 11 had one year earlier detected a thick, gaseous atmosphere over Titan, the *Voyager* space probes' controllers at the Jet Propulsion Laboratory elected for *Voyager 1* to make a close approach of Titan, and of necessity end its Grand Tour there.

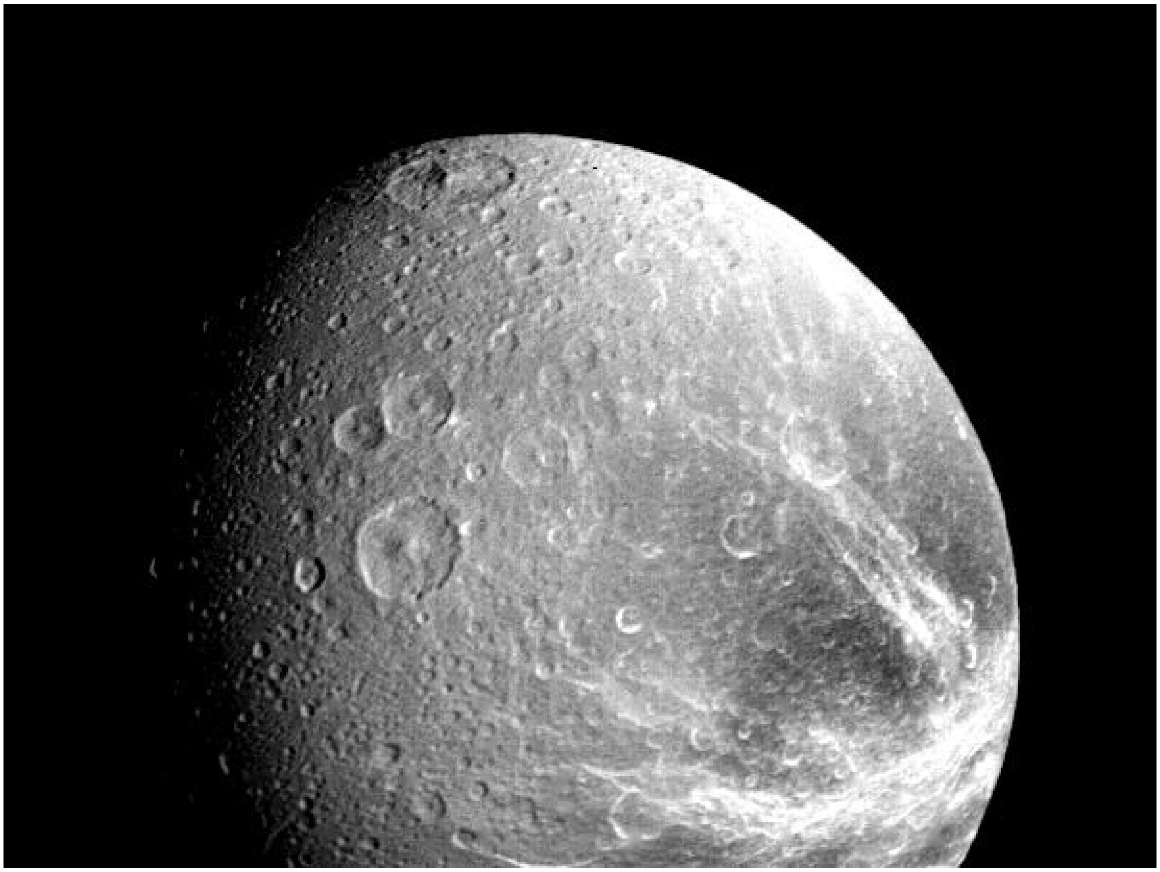
Its trajectory with a close fly-by of Titan caused an extra gravitational deflection that sent *Voyager 1* out of the plane of the Ecliptic, thus ending its planetary science mission. Voyager 1 could have been commanded onto a different trajectory, whereby the gravitational slingshot effect of Saturn's mass would have steered and boosted *Voyager 1* out to a fly-by of Pluto. However, this plutonian option was not exercised, because the other trajectory that led to the close fly-by of Titan was decided to have more scientific value and less risk.

Saturn from 5.3 million km, four days after its closest approach.

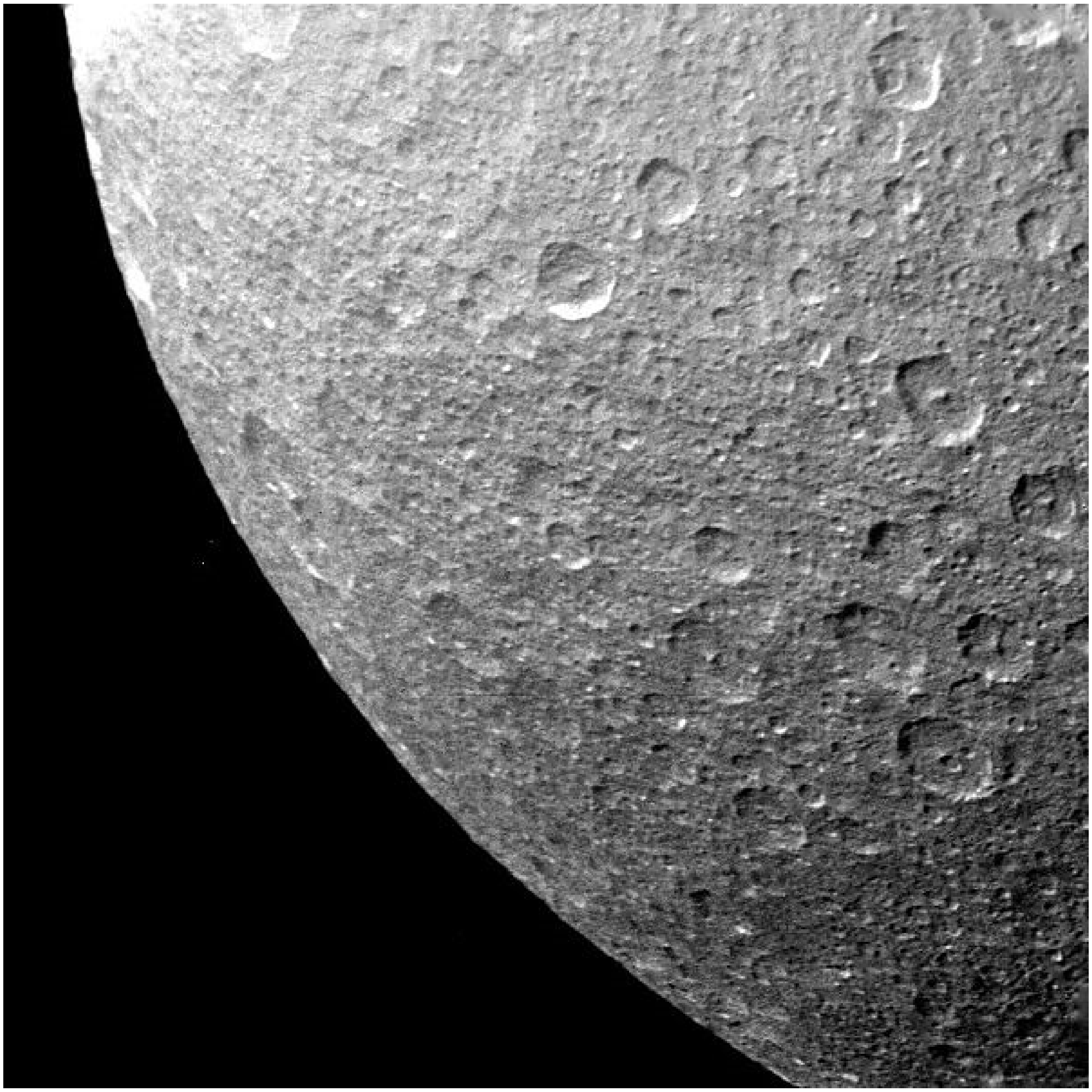


Mimas at a range of 425,000 km from *Voyager 1*.


Tethys photographed by *Voyager 1* from 1.2 million km.

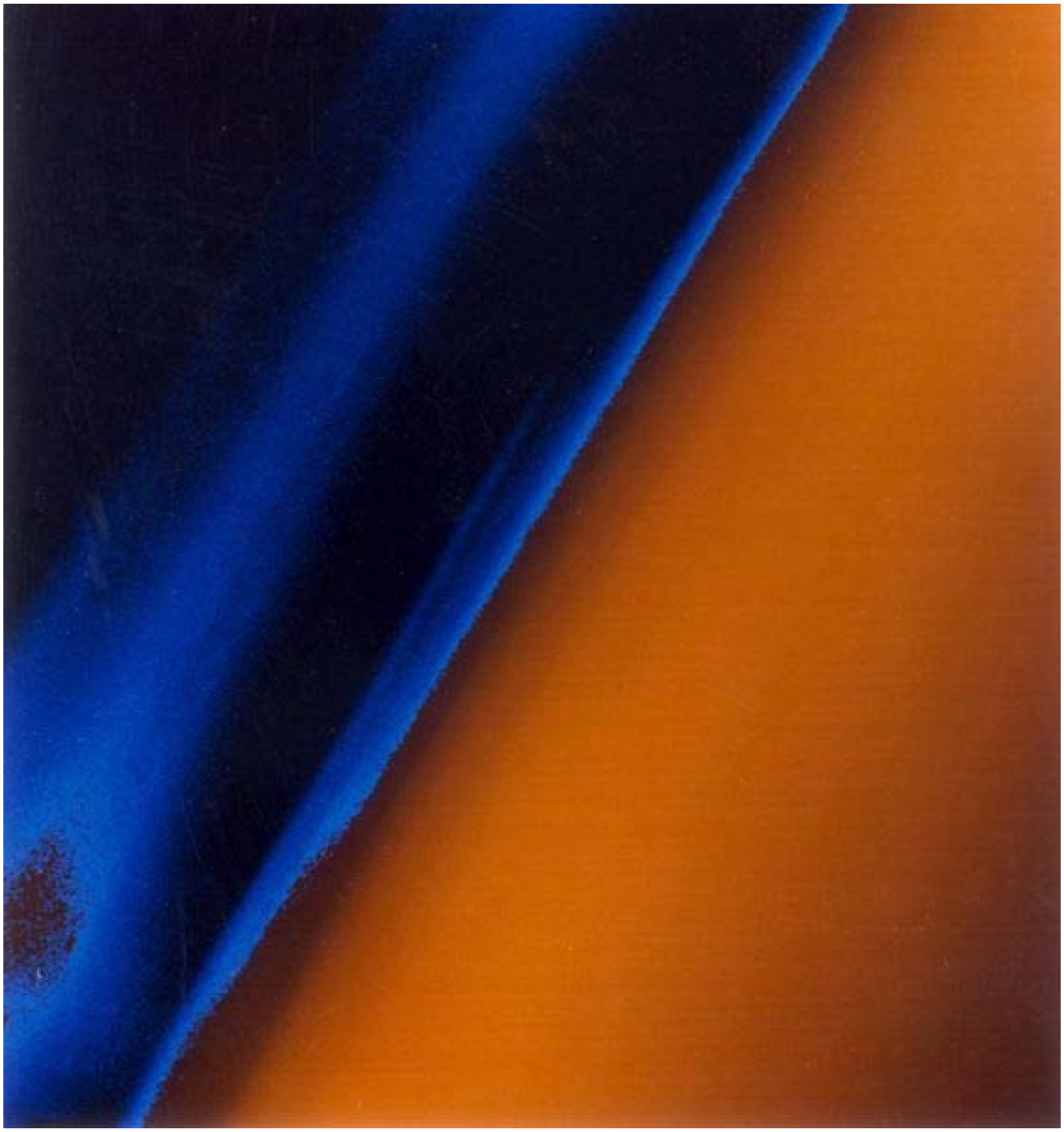


Fractured terrain on Dione.



Impact craters on the surface of Rhea appear similar to Mercury.

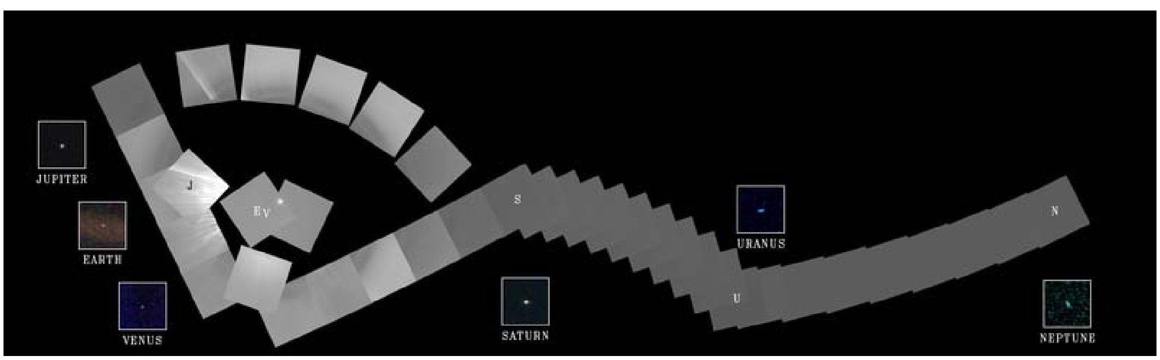
Titan's thick haze layer is shown in this enhanced *Voyager 1* image.



Layers of haze covering Saturn's satellite Titan.

Voyager 1 image of Saturn's F Ring.

Interstellar mission



The "family portrait" of the Solar system taken by Voyager 1

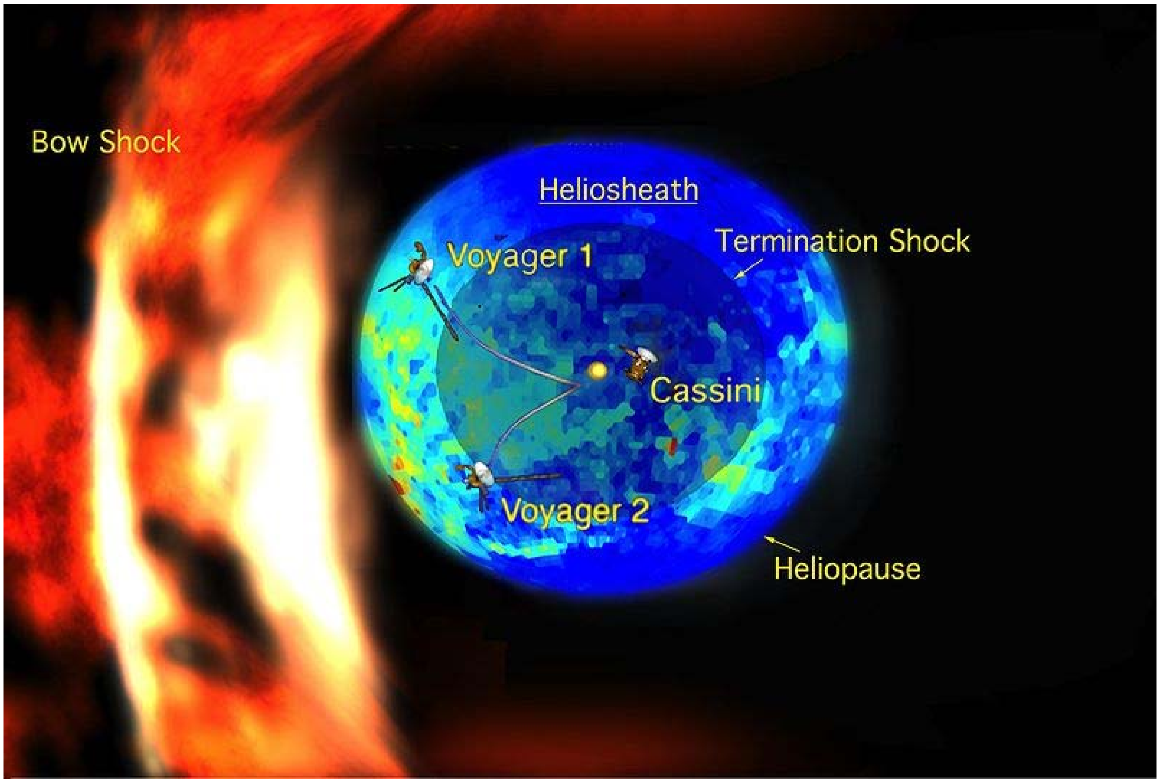
On February 14, 1990, *Voyager 1* took the first ever "family portrait" of our solar system as seen from outside, which includes the famous image known as "Pale blue dot". It is estimated that both *Voyager* craft have sufficient electrical power to operate their radio transmitters until at least 2025, which will be over 48 years after launch.

On November 17, 1998, *Voyager 1* overtook *Pioneer 10* as the most distant man-made object from Earth, at a distance of 69.419 AU. It is currently the most distant functioning space probe to receive commands and transmit information to Earth. Provided *Voyager 1* does not collide with any stellar objects, the *New Horizons* space probe will never pass it, despite being launched from Earth at a faster speed than either *Voyager* spacecraft.

The current speed of New Horizons is slightly greater than *Voyager 1* but when *New Horizons* reaches the same distance from the sun as *Voyager 1* is now, its speed will be about 13 km/s (8 miles/sec) compared to Voyager's 17 km/s (10.5 miles/sec). The close flyby of Saturn and Titan gave *Voyager 1* a massive advantage with its extra gravity assist.

Year	**End of specific capabilities as a result of the available electrical power limitations**
2007	Termination of plasma subsystem (PLS)
2008	Power off Planetary Radio Astronomy Experiment (PRA)
2010	Terminate scan platform and Ultraviolet spectrometer (UVS) observations
2015	Termination of Data Tape Recorder (DTR) operations (limited by ability to capture 1.4 kbit/s data using a 70 m/34 m antenna array. This is the minimum rate at which the DTS can read-out data.)
2016 approx	Termination of gyroscopic operations
2020	Start shutdown of science instruments (as of 2008-03-18 the order is undecided but the Low-Energy Charged Particles, Cosmic Ray Subsystem, Magnetometer, and Plasma Wave Subsystem instruments are expected to still be operating)
2025 or after	Can no longer power any single instrument.

Heliopause



Voyager 1 is currently within the heliosheath and approaching interstellar space.

As *Voyager 1* heads for interstellar space, its instruments continue to study the solar system; Jet Propulsion Laboratory scientists are using the plasma wave experiments aboard *Voyager 1* and *2* to look for the heliopause, the boundary at which the solar wind transitions into the interstellar medium.

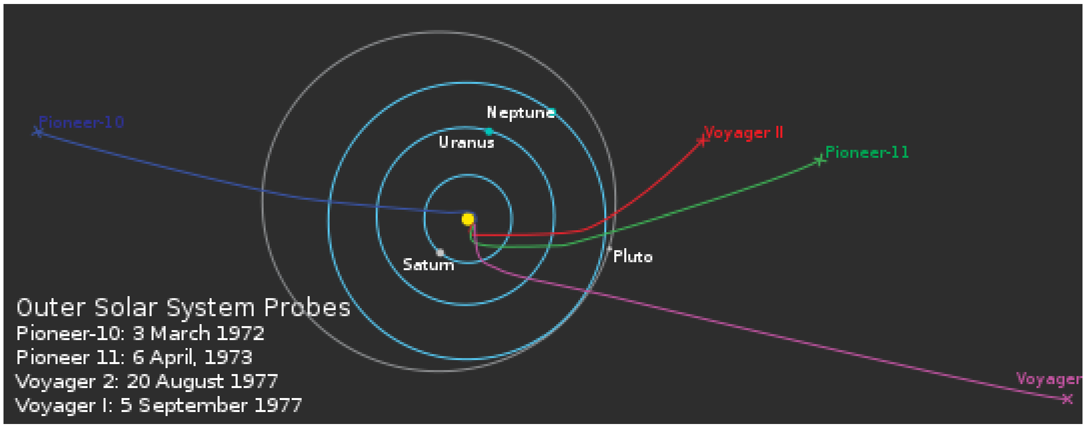
Scientists at the Johns Hopkins University Applied Physics Laboratory believe that *Voyager 1* entered the termination shock in February 2003. Some other scientists have expressed doubt, discussed in the journal *Nature* of November 6, 2003. In a scientific session at the American Geophysical Union meeting in New Orleans on the morning of May 25, 2005, Dr. Ed Stone presented evidence that *Voyager 1* crossed the termination shock in December 2004.

The issue will not be resolved until other data becomes available, since *Voyager 1*'s solar-wind detector ceased functioning in 1990. This failure has meant that termination shock detection must be inferred from the data from the other instruments on board.

However, in May 2005 a NASA press release said that consensus was that *Voyager 1* was now in the heliosheath. Scientists anticipate that the craft will reach the heliopause in 2015.

Voyager 1 is the farthest human-made object from Earth, traveling away from both the Earth and the Sun at a relatively faster speed than any other probe.

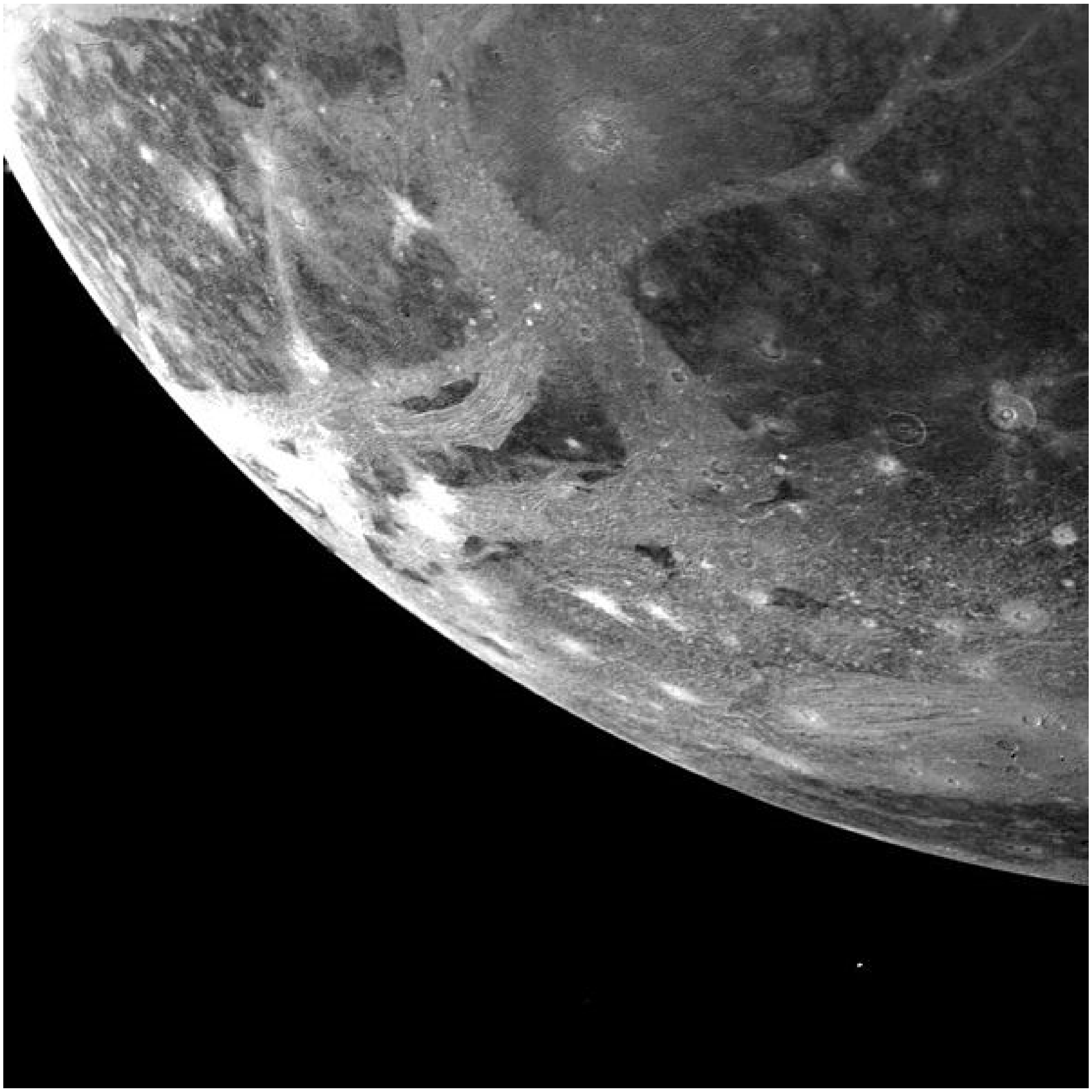
Current status

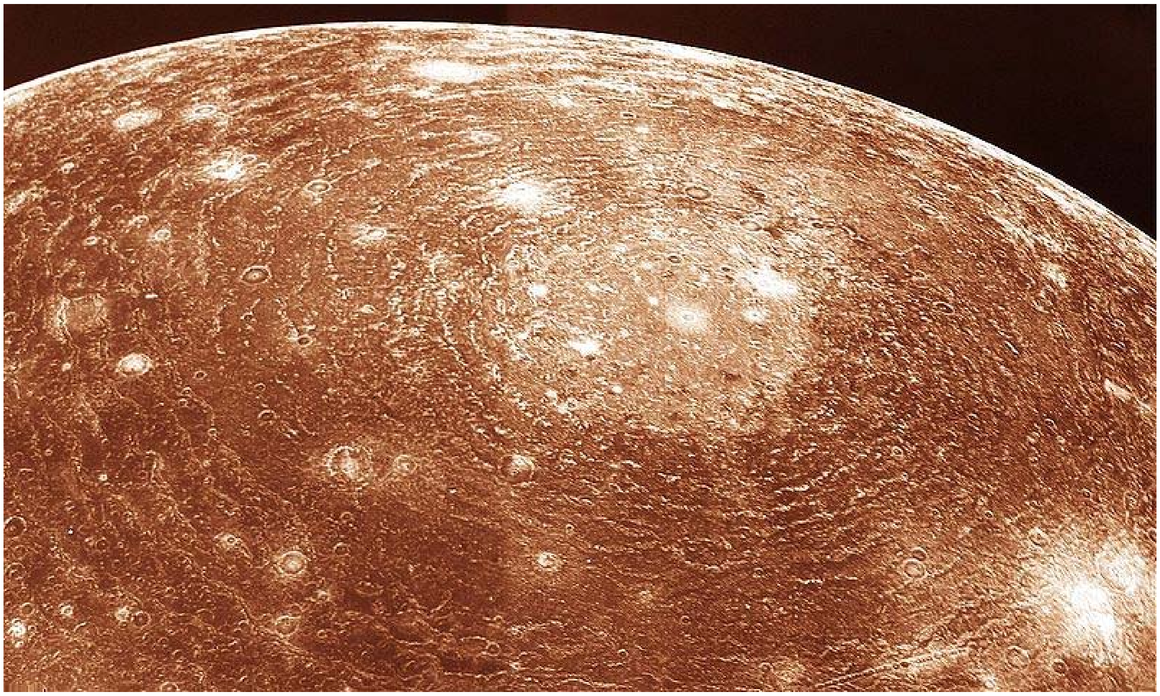


Location and trajectories of Pioneer and Voyager spacecraft, as of July 7, 2007. Note Voyager 2 is farther than Pioneer 11 and only appears closer here due to its -55 degree declination, and that Voyager 1's position is drawn too far away.

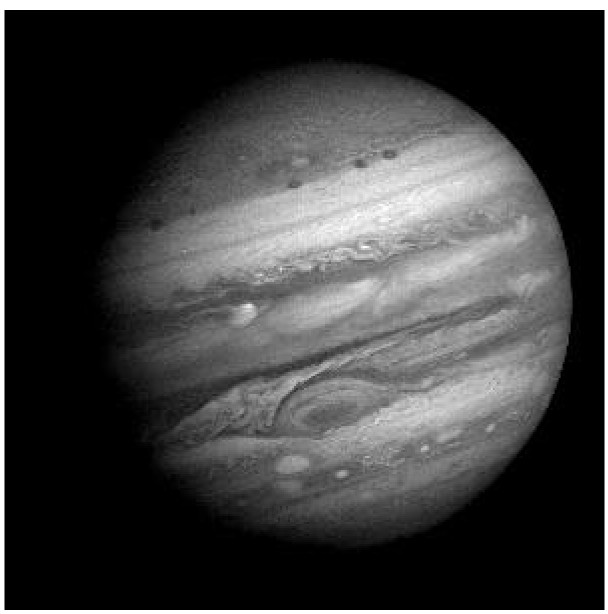
As of **February 17th, 2011**, *Voyager 1* was about 116.205AU (17.242 billion km, or 10.788 billion miles) or about 0.00183 of a light-year from the Sun. Radio signals traveling at the speed of light between Voyager 1 and Earth take 16.14 hours to cross the distance between the two. (To compare, Proxima Centauri, the closest star to our Sun, is about 4.2 light-years distant = 265 thousand AU) *Voyager 1's* current relative velocity is 17.064 km/s, or 61,452 kilometres per hour (38,185 mph). This calculates as 3.6 AU per year, about 10% faster than *Voyager 2*. At this velocity, 73,600 years would pass before reaching the nearest star, Proxima Centauri, were the spacecraft traveling in the direction of that star.

Europa as seen from *Voyager 1* at a distance of 2.8 million km.


Icy surface of Ganymede as photographed from 253,000 km.



Valhalla crater on Callisto as imaged by *Voyager 1* in 1979.



Voyager 1 time lapse movie of Jupiter approach. Full size video here

Voyager 1 is not heading towards any particular star, but in about 40,000 years it will pass within 1.6 light years of the star AC+79 3888 in the constellation Camelopardalis. That star is generally moving towards our Solar System at about 119 kilometers per second.

The spacecraft is at 11.95° declination and 17.172 hours right ascension, placing it in the constellation Ophiuchus as observed from the Earth. NASA continues its daily tracking of *Voyager 1* with its Deep Space Network. This network measures both the elevation and azimuth angles of the incoming radio waves from *Voyager 1*, and it also measures the distance from the Earth to *Voyager 1*.

On **March 31, 2006**, the amateur radio operators from AMSAT in Germany tracked and received radio waves from *Voyager 1* using the 20-meter (66 ft) dish at Bochum with a long integration technique. Retrieved data was checked and verified against data from the Deep Space Network station at Madrid, Spain. This is believed to be the first such tracking of *Voyager 1*.

On **December 13, 2010**, it was confirmed that *Voyager 1* passed the reach of the solar wind emanating from the Sun. It is suspected that solar wind at this distance turns sideways due to interstellar wind pushing against the heliosphere. Since June 2010, detection of solar wind has been consistently at zero, providing conclusive evidence of the event. The meridional (north-south) speed of the solar wind, which is suspected to have increased, cannot be inferred in Voyager 1's current configuration. On this date, the spacecraft was approximately 17.3 billion km (10.8 billion miles) from the Sun

On **November 19, 2015**, *Voyager 1* is projected to be approximately 133.15 Astronomical Units from the Sun.

Information regarding updates about Voyager 1 (as well as Voyager 2, Pioneer 10, Pioneer 11 and New Horizons) are available online at Spacecraft Escaping the Solar System and Weekly Mission Reports.

Chapter- 4

Voyager 2

Voyager 2

Voyager spacecraft

Operator	NASA / JPL
Mission type	Flyby
Flyby of	Jupiter, Saturn, Uranus, Neptune
Launch date	1977-08-20 14:29:00 UTC (33 years, 5 months, and 30 days ago)
Launch vehicle	Titan IIIE / Centaur
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In Progress (Interstellar mission) (31 years, 7 months, and 10 days elapsed)

	Jupiter flyby *(completed 1979-08-05)* Saturn flyby *(completed 1981-09-25)* Uranus flyby *(completed 1986-02-25)* Neptune flyby *(completed 1989-10-02)*
COSPAR ID	1977-076A
Homepage	NASA *Voyager* website
Mass	721.9 kg (1,592 lb)
Power	420 W (3 RTGs)

The ***Voyager 2*** spacecraft is a 722-kilogram (1,592 lb) robotic space probe launched by NASA on August 20, 1977 to study the outer Solar System and eventually interstellar space. Operating for 33 years, 5 months, and 30 days as of today's date (19 February 2011), the spacecraft receives routine commands and transmits data back to the Deep Space Network. Currently in extended mission, the spacecraft is tasked with locating and studying the boundaries of the Solar System, including the Kuiper belt, the heliosphere and interstellar space. The primary mission ended December 31, 1989 after encountering the Jovian system in 1979, Saturnian system in 1980, Uranian system in 1986, and the Neptunian system in 1989. It was the first probe to provide detailed images of the outer ice giants.

Mission background

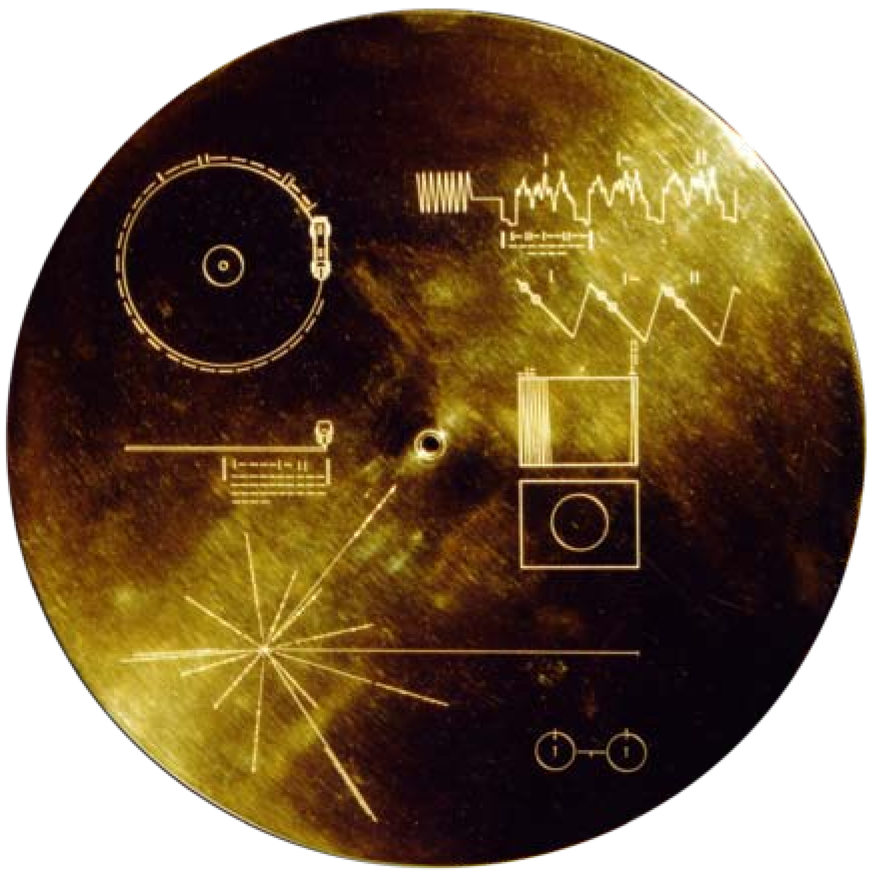
History

Conceived in the 1960s, a Grand Tour proposal to study the outer planets, prompted NASA to begin work on a mission in the early 1970s. The development of the interplanetary probes coincided with an alignment of the planets, making possible a mission to the outer Solar System by taking advantage of the then-new technique of gravity assist.

It was determined that utilizing gravity assists would enable a single probe to visit the four gas giants (Jupiter, Saturn, Uranus, and Neptune) while requiring a minimal amount of propellant and a shorter transit duration between planets. Originally, *Voyager 2* was planned as *Mariner 12* of the Mariner program however, due to congressional budget cuts, the mission was scaled back to be a flyby of Jupiter and Saturn, and renamed the Mariner Jupiter-Saturn probes. As the program progressed, the name was later changed to Voyager as the probe designs began to differ greatly from previous Mariner missions.

Upon a successful flyby of the Saturnian moon Titan, by Voyager 1, *Voyager 2* would get a mission extension to send the probe on towards Uranus and Neptune.

Golden record



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President of the United States, and the children of the Planet Earth) and a medley, "Sounds of Earth", that includes the sounds of whales, a baby crying, waves breaking on a shore, and a variety of music.

Spacecraft design

Constructed by the Jet Propulsion Laboratory, *Voyager 2* included 16 hydrazine thrusters, three-axis stabilization, gyroscopes and celestial referencing instruments (sun sensor/Canopus Star Tracker) to maintain pointing of the high-gain antenna toward Earth. Collectively these instruments are part of the Attitude and Articulation Control Subsystem (**AACS**) along with redundant units of most instruments and 8 backup thrusters. The spacecraft also included 11 scientific instruments to study celestial objects as it traveled through space.

Communications

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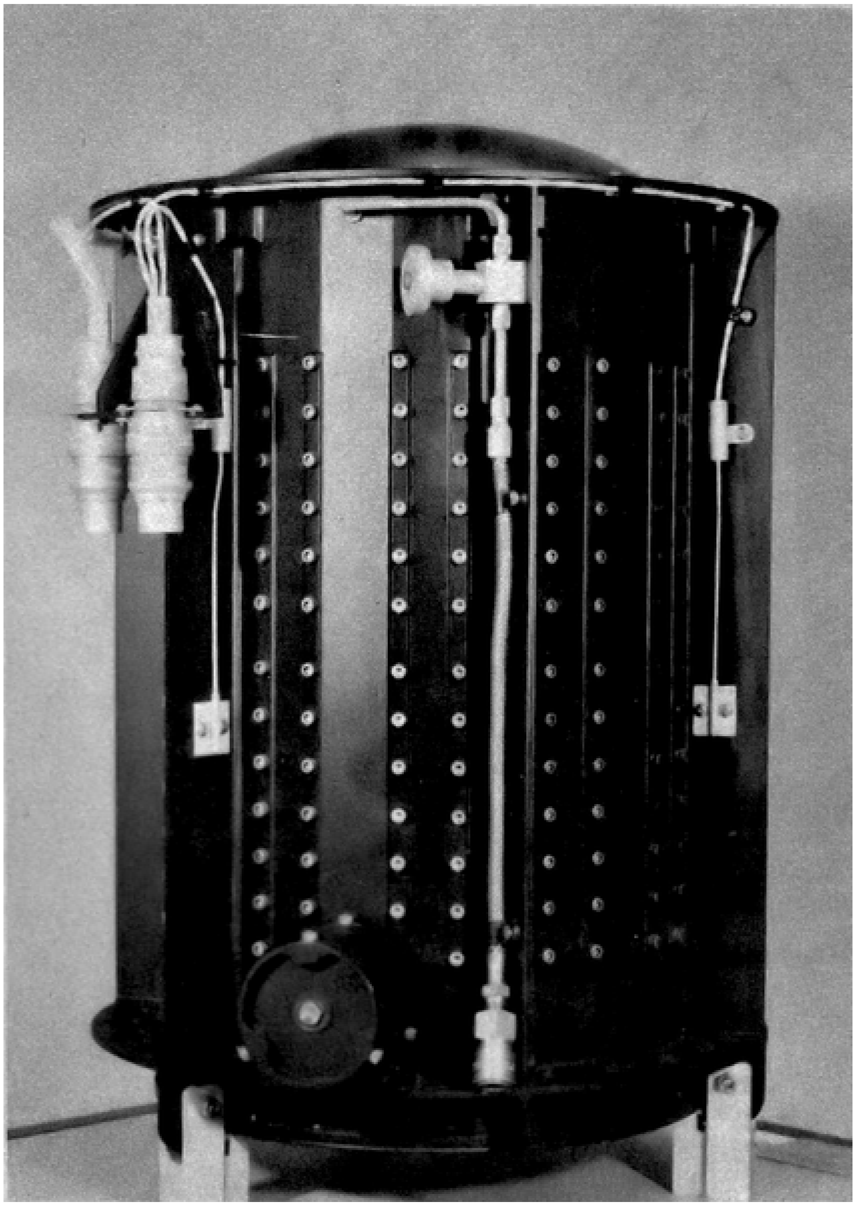
Power



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Scientific instruments

Expand

Instrument Name	Abr.	Description
Imaging Science System **(disabled)**	**(ISS)**	Utilizes a two-camera system (narrow-angle/wide-angle) to provide imagery of Jupiter, Saturn and other objects along the trajectory. **Filters**

Narrow Angle Camera Filters			
Name	**Wavelength**	**Spectrum**	**Sensitivity**
Clear	280nm - 640nm		
UV	280nm - 370nm		
Violet	350nm - 450nm		
Blue	430nm - 530nm		
'	'		'
Green	530nm - 640nm		
'	'		'
Orange	590nm - 640nm		
'	'		'

Wide Angle Camera Filters			
Name	**Wavelength**	**Spectrum**	**Sensitivity**
Clear	280nm - 640nm		
'	'		'
Violet	350nm - 450nm		
Blue	430nm - 530nm		
CH_4-U	536nm - 546nm		
Green	530nm - 640nm		
Na-D	588nm - 590nm		
Orange	590nm - 640nm		
CH_4-JST	614nm - 624nm		

- **Principal investigator:** Bradford Smith / University of Arizona (PDS/PRN website)
- **Data:** PDS/PDI data catalog, PDS/PRN data catalog

Radio Science System (**disabled**) (**RSS**)

Utilized the telecommunications system of the Voyager spacecraft to determine the physical properties of planets and satellites (ionospheres, atmospheres, masses, gravity fields, densities) and the amount and size distribution of material in Saturn's rings and the ring dimensions.

- **Principal investigator:** G. Tyler / Stanford University PDS/PRN overview
- **Data:** PDS/PPI data catalog, PDS/PRN data catalog **(**VG_2803**)**, NSSDC Saturn data archive

Infrared Interferometer Spectrometer (**disabled**) (**IRIS**)

Investigates both global and local energy balance and atmospheric composition. Vertical temperature profiles are also obtained from the planets and satellites as well as the composition, thermal properties, and size of particles in Saturn's rings.

- **Principal investigator:** Rudolf Hanel / NASA Goddard Space Flight Center (PDS/PRN website)
- **Data:** PDS/PRN data catalog, PDS/PRN expanded data catalog **(**VGIRIS_0001, VGIRIS_002**)**

Ultraviolet Spectrometer (**disabled**) (**UVS**)

Designed to measure atmospheric properties, and to measure radiation.

- **Principal investigator:** A. Broadfoot / University of Southern California (PDS/PRN website)
- **Data:** PDS/PRN data catalog

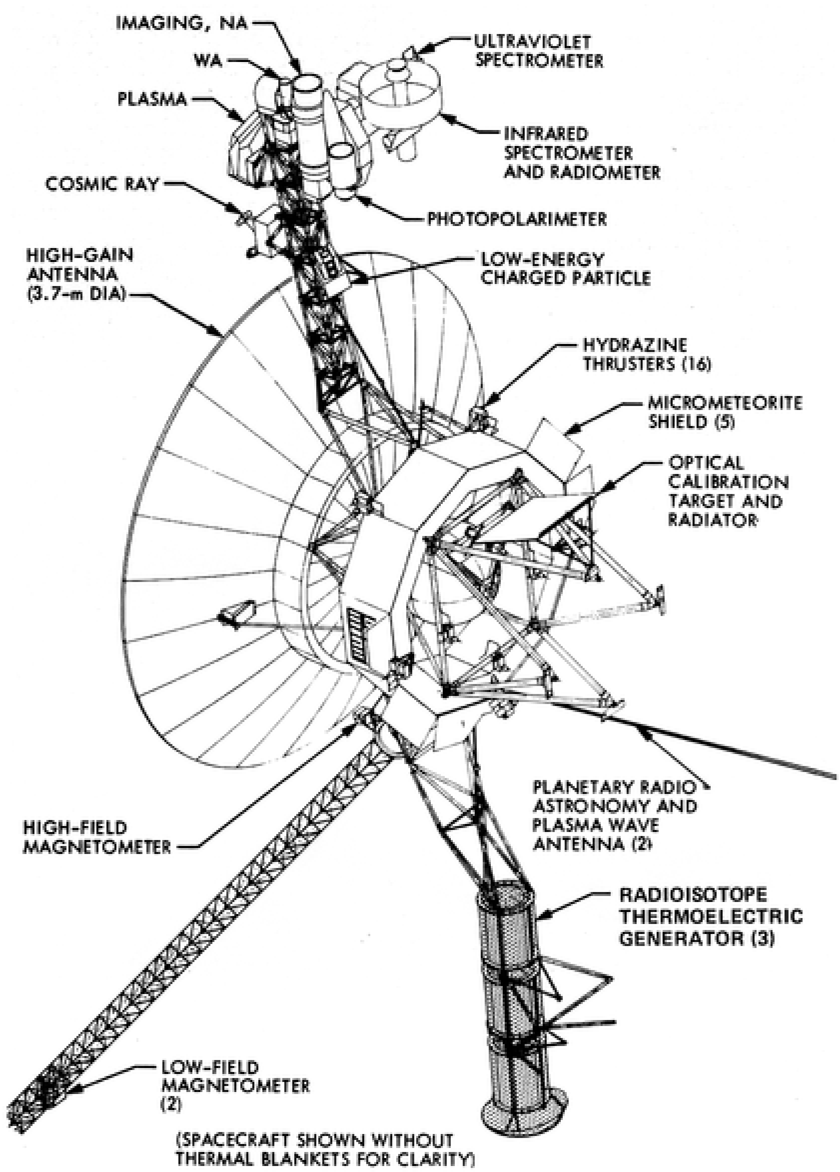
Triaxial Fluxgate Magnetometer (**active**) (**MAG**)

Designed to investigate the magnetic fields of Jupiter and Saturn, the solar-wind interaction with the magnetospheres of these planets, and the interplanetary magnetic field out to the solar wind boundary with the interstellar magnetic field and beyond, if crossed.

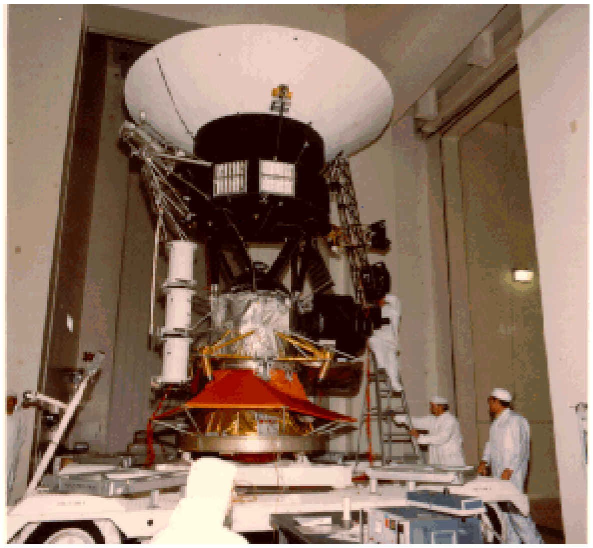
- **Principal investigator:** Norman Ness / NASA Goddard Space Flight Center (website)
- **Data:** PDS/PPI data catalog, NSSDC data archive

Plasma Spectrometer (**active**)	(**PLS**)	Investigates the macroscopic properties of the plasma ions and measures electrons in the energy range from 5 eV to 1 keV. • **Principal investigator:** John Richardson / MIT (website) • **Data:** PDS/PPI data catalog, NSSDC data archive
Low Energy Charged Particle Instrument (**active**)	(**LECP**)	Measures the differential in energy fluxes and angular distributions of ions, electrons and the differential in energy ion composition. • **Principal investigator:** Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website) • **Data:** UMD data plotting, PDS/PPI data catalog, NSSDC data archive
Cosmic Ray System (**active**)	(**CRS**)	Determines the origin and acceleration process, life history, and dynamic contribution of interstellar cosmic rays, the nucleosynthesis of elements in cosmic-ray sources, the behavior of cosmic rays in the interplanetary medium, and the trapped planetary energetic-particle environment. • **Principal investigator:** Edward Stone / CalTech / NASA Goddard Space Flight Center (website) • **Data:** NSSDC data archive
Planetary Radio Astronomy Investigation (**disabled**)	(**PRA**)	Utilizes a sweep-frequency radio receiver to study the radio-emission signals from Jupiter and Saturn. • **Principal investigator:** James Warwick / University of Colorado • **Data:** PDS/PPI data catalog
Photopolarimeter System (**disabled**)	(**PPS**)	Utilized a telescope with a polarizer to gather information on surface texture and composition of Jupiter and Saturn and information on atmospheric scattering properties and density for both planets. • **Principal investigator:** Arthur Lane / JPL (PDS/PRN website) • **Data:** PDS/PRN data catalog
Plasma Wave System (**partially disabled**)	(**PWS**)	Provides continuous, sheath-independent measurements of the electron-density profiles at Jupiter and Saturn as well as basic information on local wave-particle interaction, useful in studying the magnetospheres. • **Principal investigator:** Donald Gurnett / University of Iowa (website) • **Data:** PDS/PPI data catalog, NSSDC data archive

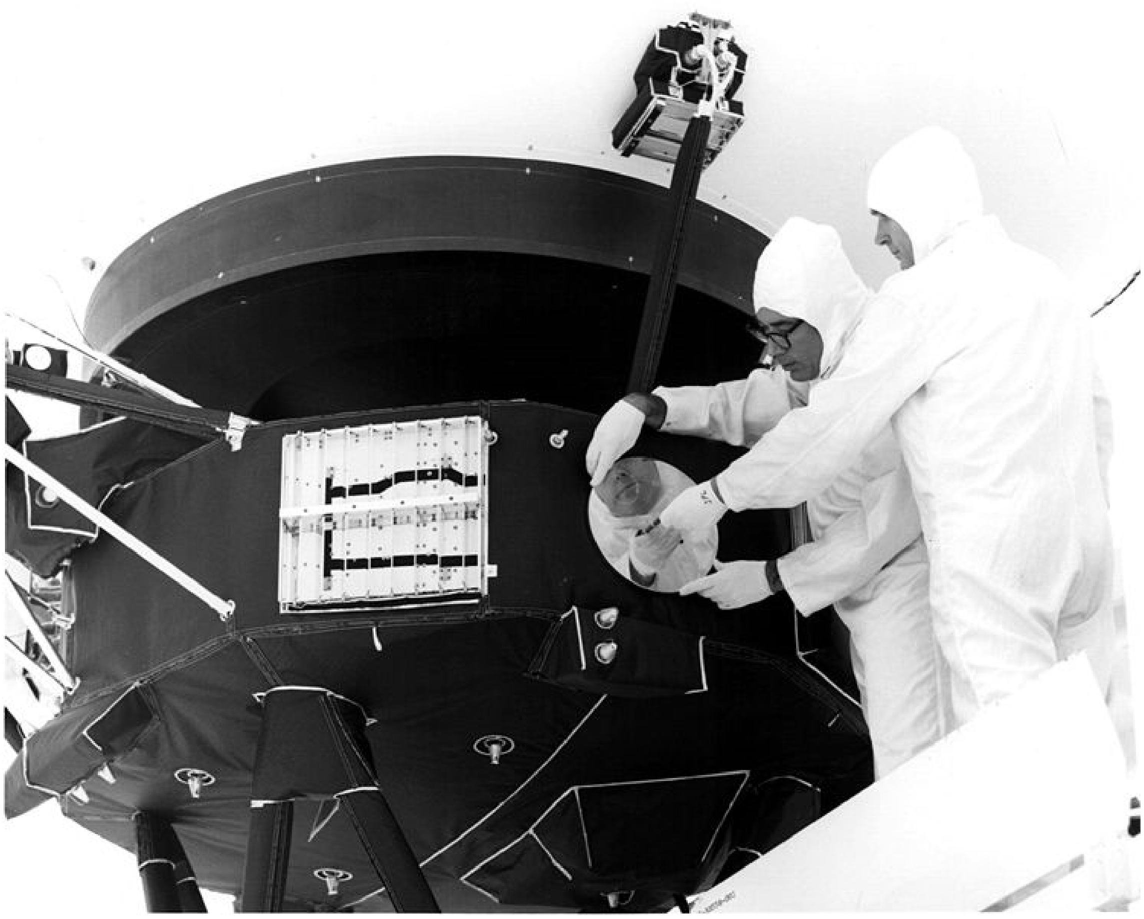
Images of the spacecraft



Voyager spacecraft diagram.



Voyager in transport to a solar thermal test chamber.



Gold-Plated Record is attached to *Voyager*.

Voyager 2 awaiting payload entry into a Titan/Centaur-6 rocket.

Timeline of travel

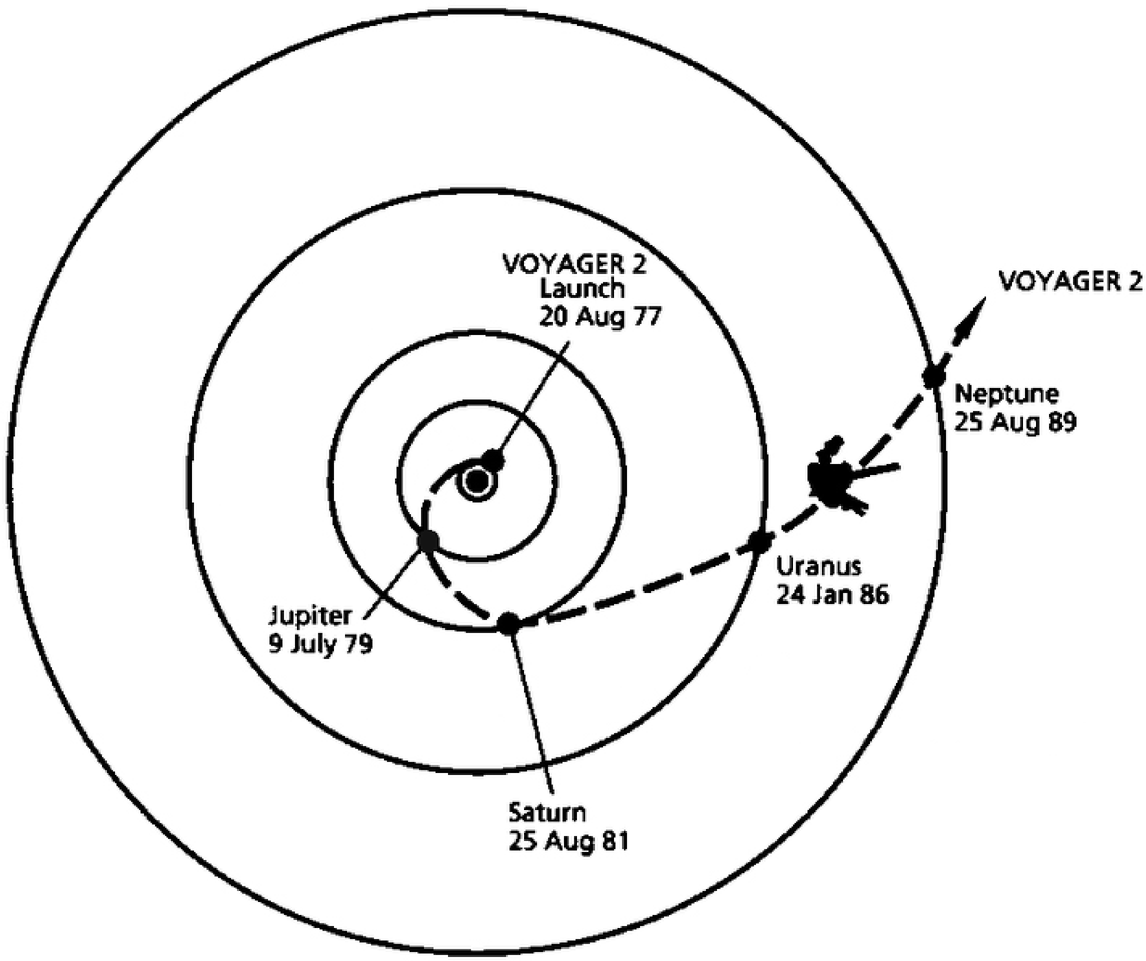
Date	Event
1977-08-20	Spacecraft launched at 14:29:00 UTC.
1977-12-10	Entered asteroid belt.
1977-12-19	Voyager 1 overtakes *Voyager 2*.
1978-06-	Primary radio receiver fails. Remainder of mission flown using backup.
1978-10-21	Exited asteroid belt
1979-04-25	Start Jupiter observation phase **Time** **Event**
1981-06-05	Start Saturn observation phase. **Time** **Event**
1985-11-04	Start Uranus observation phase. **Time** **Event**
1985-11-04	Start Neptune observation phase. **Time** **Event**
1989-10-02	Begin Voyager Interstellar Mission.

Mission profile

Launch and trajectory

The *Voyager 2* probe was launched on August 20, 1977, by the National Aeronautics and Space Administration from Space Launch Complex 41 at Cape Canaveral, Florida, aboard a Titan IIIE/Centaur launch vehicle. Two weeks later, the twin *Voyager 1* probe would be launched on September 5, 1977. However, *Voyager 1* would reach both Jupiter and Saturn sooner, as *Voyager 2* had been launched into a longer, more circular trajectory.

Voyager 2 launch on August 20, 1977 with a Titan IIIE/Centaur.



Trajectory of *Voyager 2* primary mission.

Encounter with Jupiter

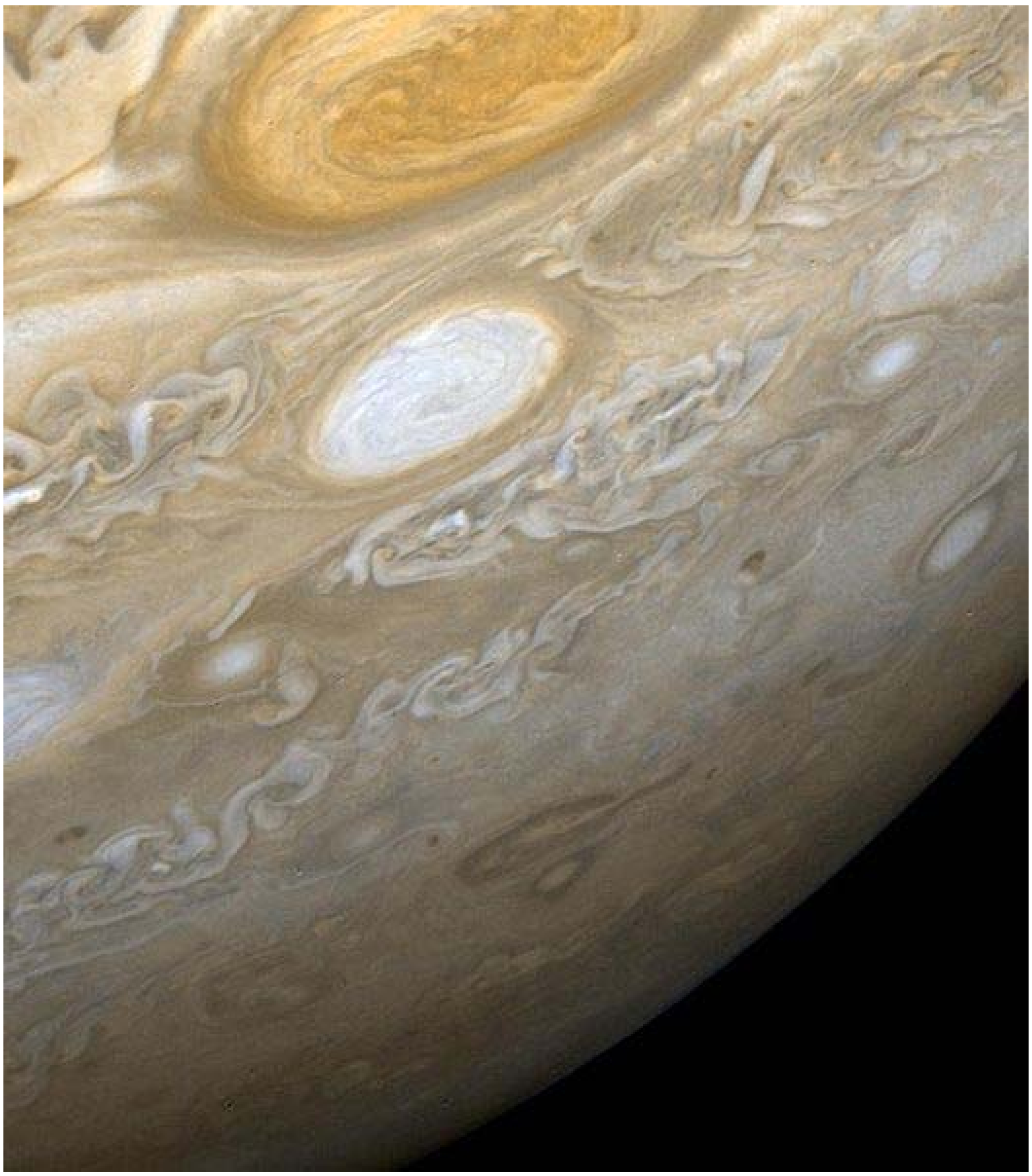
The closest approach to Jupiter occurred on July 9, 1979. It came within 570,000 km (350,000 miles) of the planet's cloud tops. It discovered a few rings around Jupiter, as well as volcanic activity on the moon Io.

The Great Red Spot was revealed as a complex storm moving in a counterclockwise direction. An array of other smaller storms and eddies were found throughout the banded clouds.

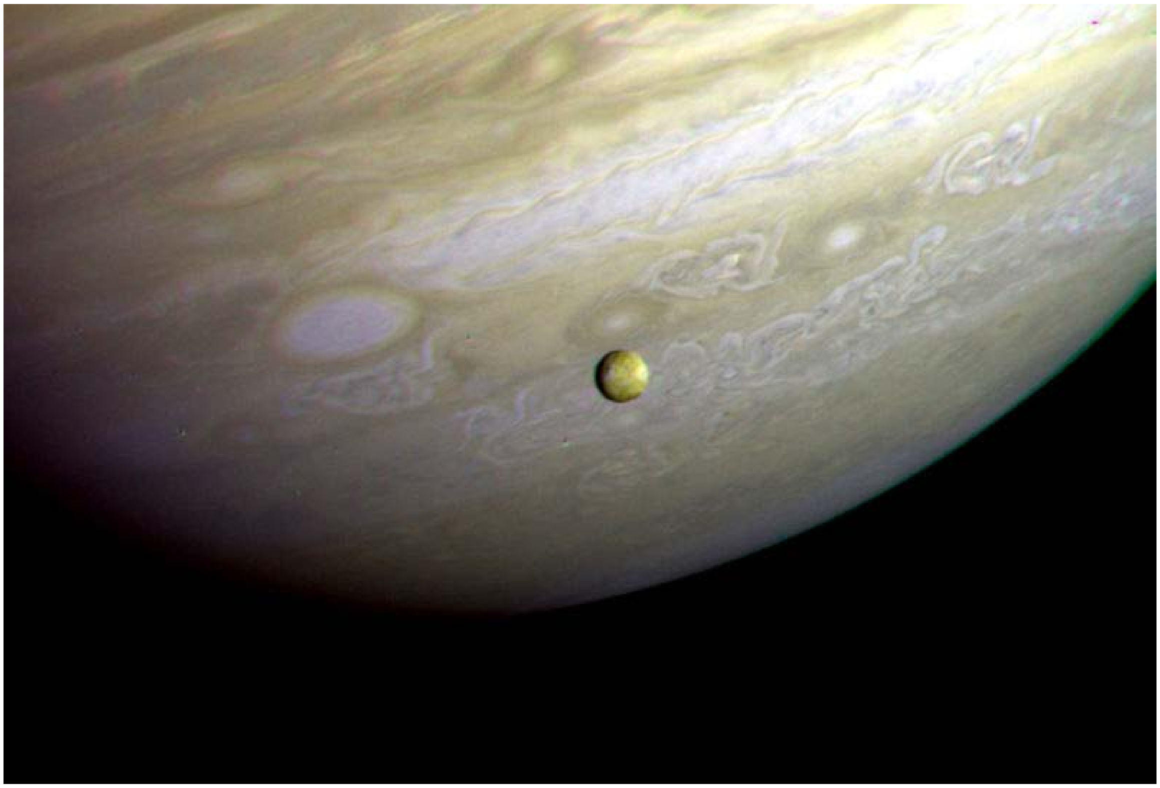
Discovery of active volcanism on the moon Io was easily the greatest unexpected discovery at Jupiter. It was the first time active volcanoes had been seen on another body in the Solar System. Together, the Voyagers observed the eruption of nine volcanoes on Io, and there is evidence that other eruptions occurred between the two Voyager fly-bys.

The moon Europa displayed a large number of intersecting linear features in the low-resolution photos from *Voyager 1*. At first, scientists believed the features might be deep cracks, caused by crustal rifting or tectonic processes. The closer high-resolution photos from *Voyager 2*, however, left scientists puzzled: The features were so lacking in topographic relief that as one scientist described them, they "might have been painted on with a felt marker." Europa is internally active due to tidal heating at a level about one-tenth that of Io. Europa is thought to have a thin crust (less than 30 kilometers or 18 miles thick) of water ice, possibly floating on a 50-kilometer-deep (30 mile) ocean.

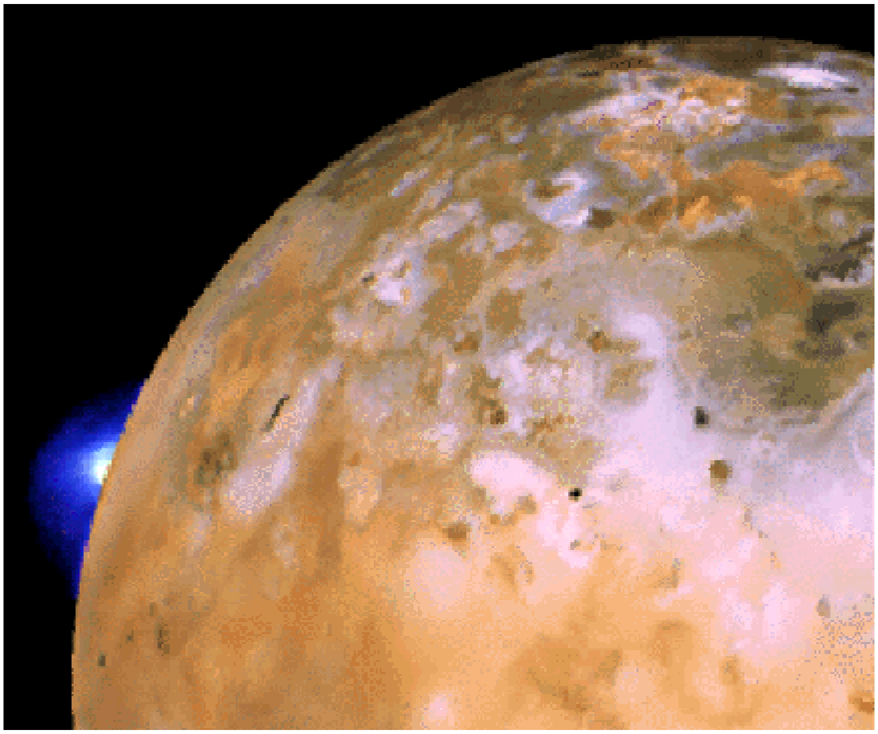
Two new, small satellites, Adrastea and Metis, were found orbiting just outside the ring. A third new satellite, Thebe, was discovered between the orbits of Amalthea and Io.



The Great Red Spot photographed during the *Voyager 2* flyby of Jupiter.



A transit of Io across Jupiter, July 9, 1979.



Eruption of a volcano on Io, photographed by Voyager 2.

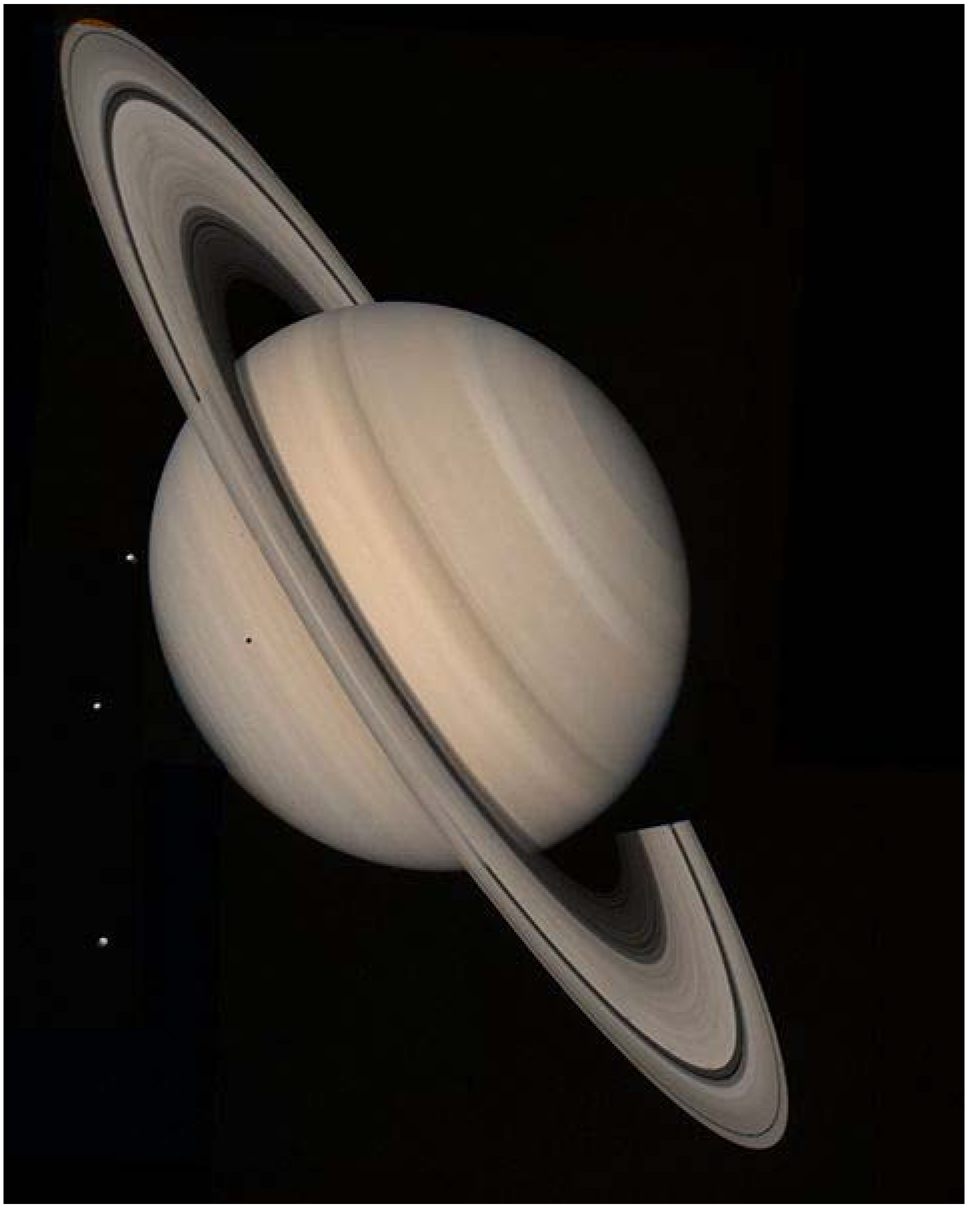
A color mosaic of Europa.

Encounter with Saturn

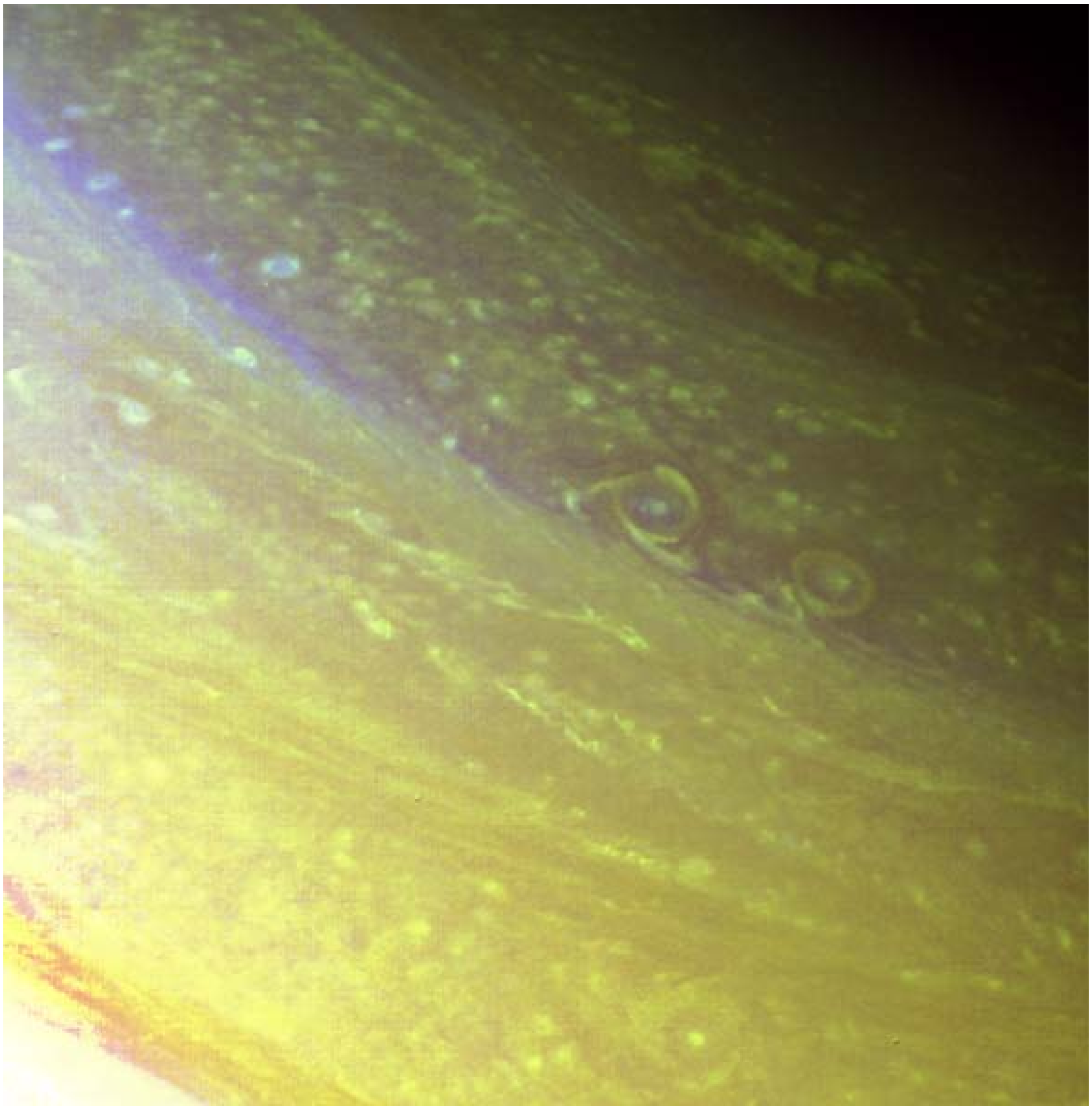
The closest approach to Saturn occurred on August 26, 1981.

While passing behind Saturn (as viewed from Earth), *Voyager 2* probed Saturn's upper atmosphere with its radio link to gather information on atmospheric temperature and density profiles. *Voyager 2* found that at the highest pressure levels (seven kilopascals of pressure), Saturn's temperature was 70 kelvins (−203 °C), while at the deepest levels measured (120 kilopascals) the temperature increased to 143 K (−130 °C). The north pole was found to be 10 kelvins cooler, although this may be seasonal.

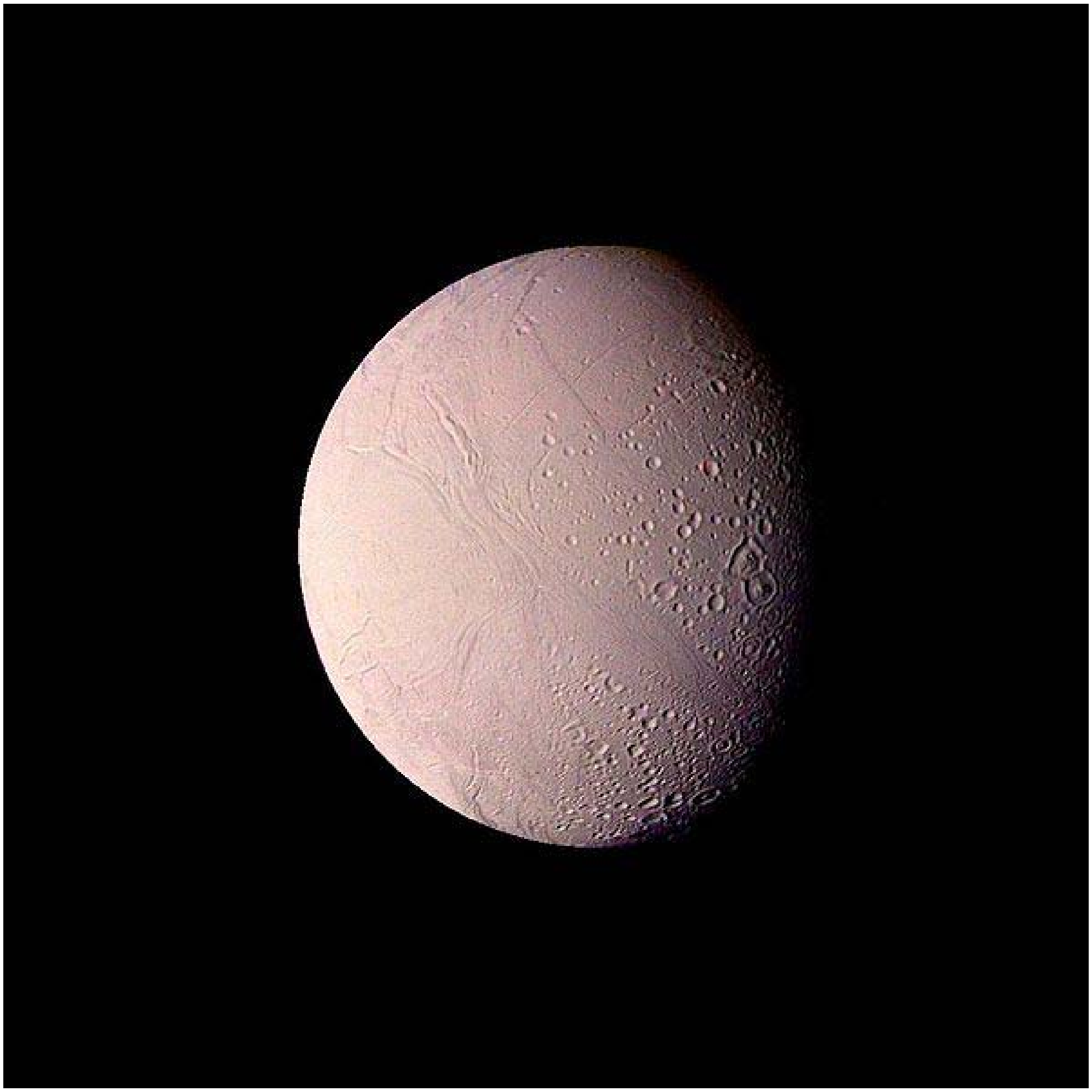
After the fly-by of Saturn, the camera platform of *Voyager 2* locked up briefly, putting plans to officially extend the mission to Uranus and Neptune in jeopardy. Fortunately, the mission's engineers were able to fix the problem (caused by an overuse that temporarily depleted its lubricant), and the *Voyager 2* probe was given the go-ahead to explore the Uranian system.



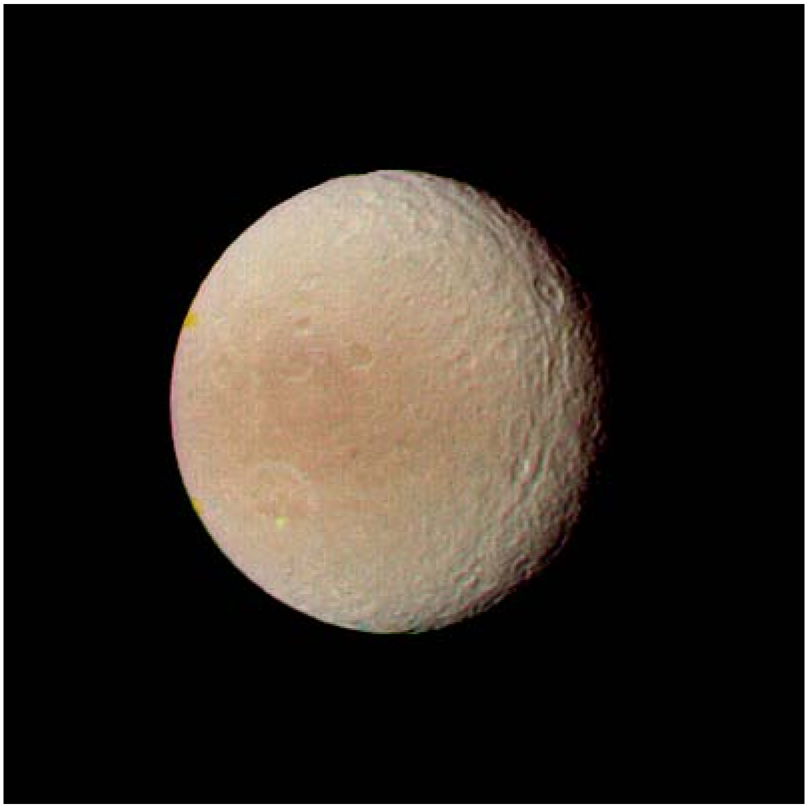
Voyager 2 Saturn approach view.



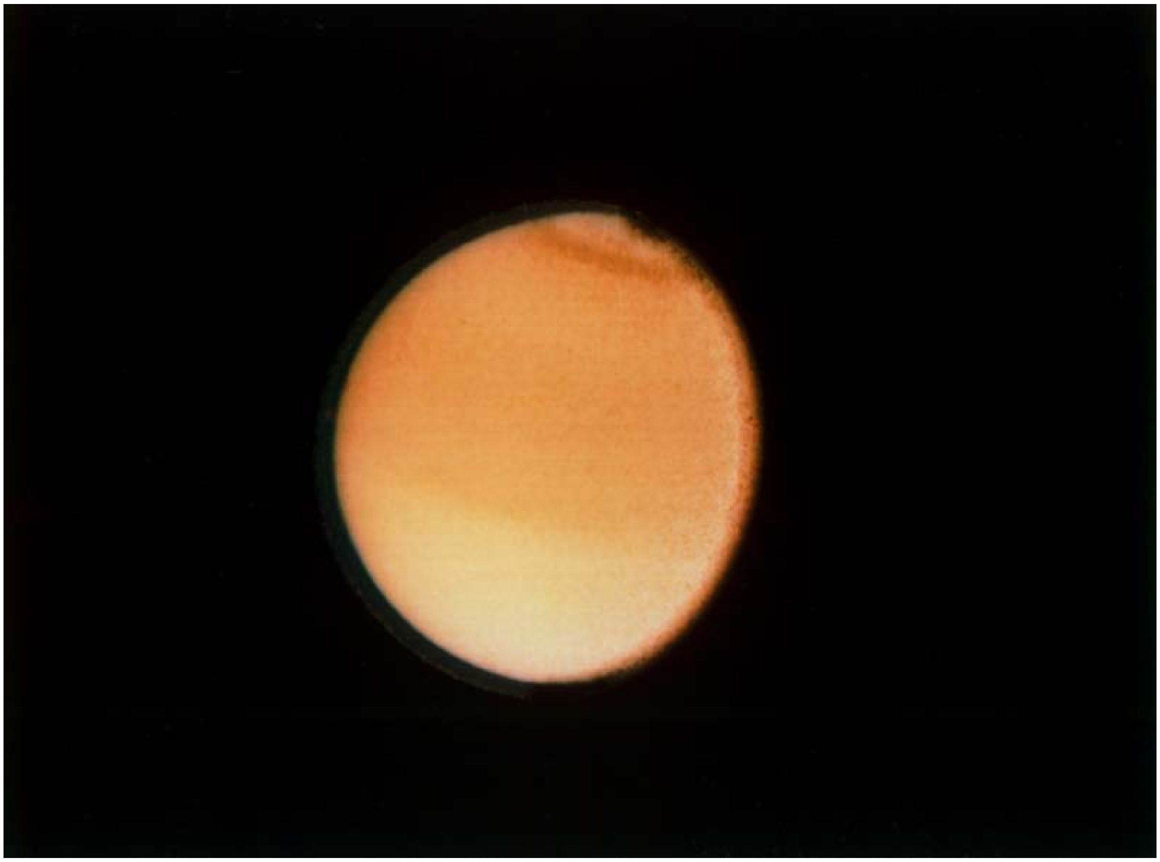
North, polar region of Saturn imaged in orange and UV filters.



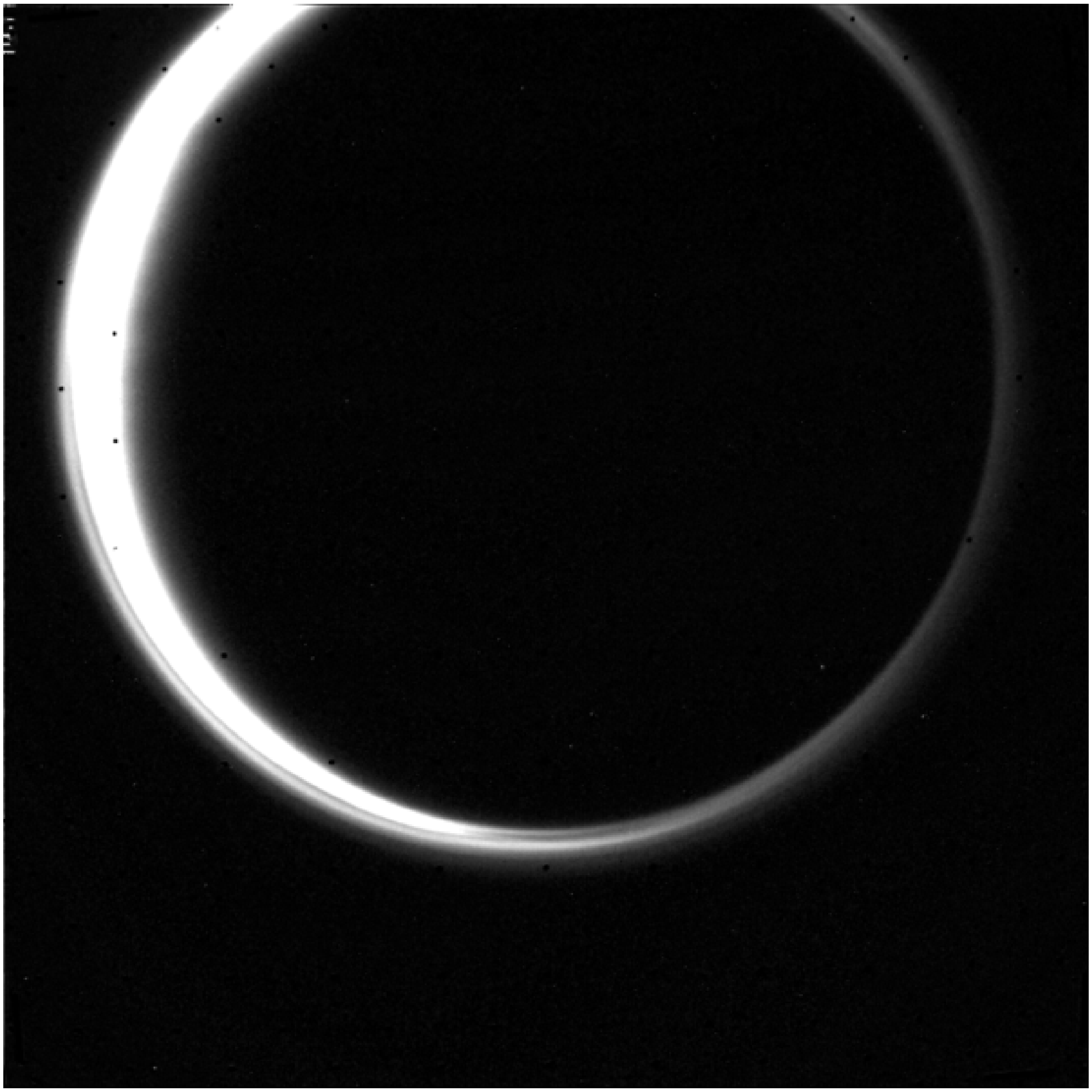
Color image of Enceladus showing terrain of widely varying ages.



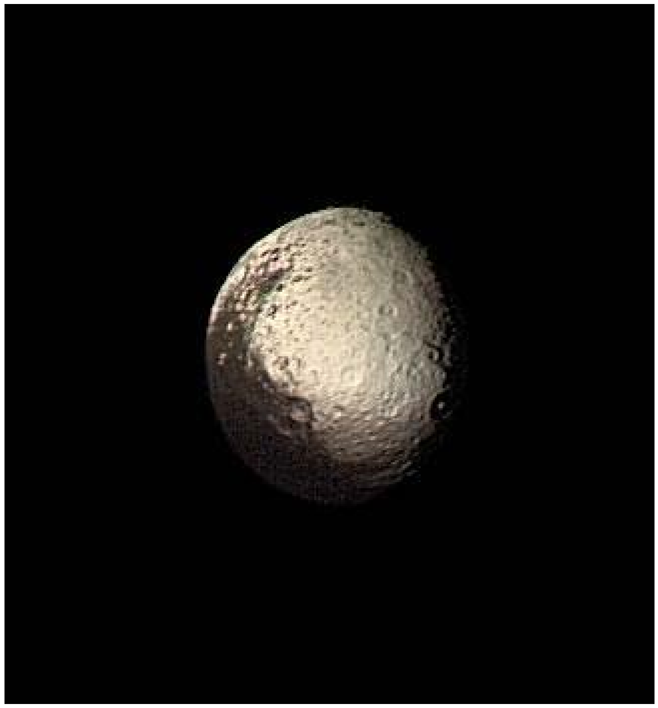
Cratered surface of Tethys at 594,000 km.



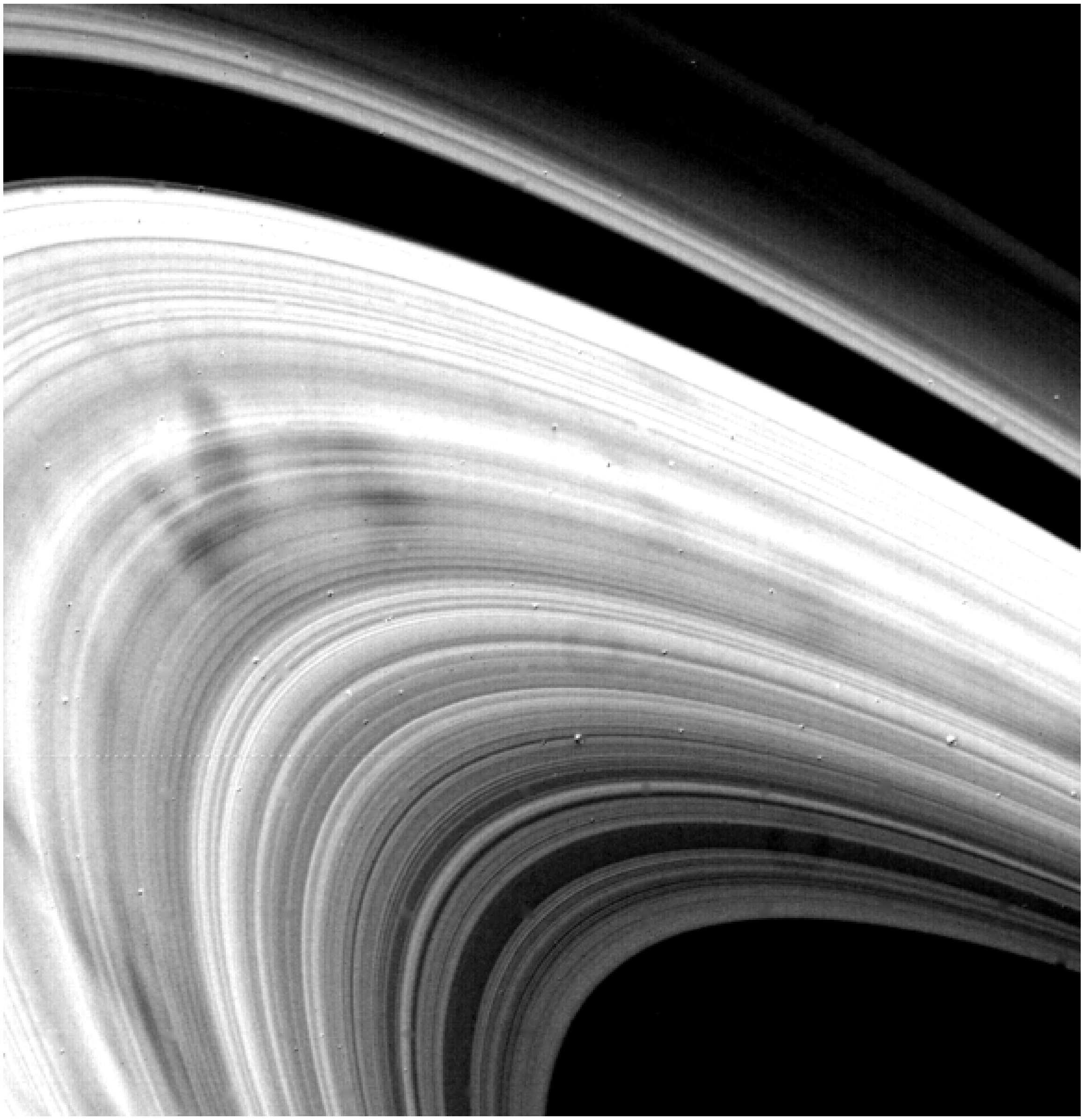
Atmosphere of Titan imaged from 2.3 million km.



Titan occultation of the Sun from 0.9 million km.



Two-toned Iapetus, August 22, 1981.



"Spoke" features observed in the rings of Saturn.

Encounter with Uranus

The closest approach to Uranus occurred on January 24, 1986, when *Voyager 2* came within 81,500 kilometers (50,600 miles) of the planet's cloud tops. *Voyager 2* also discovered 10 previously unknown moons of Uranus; studied the planet's unique atmosphere, caused by its axial tilt of 97.8°; and examined the Uranian ring system.

Uranus is the third largest (Neptune has a larger mass, but a smaller volume) planet in the Solar System. It orbits the Sun at a distance of about 2.8 billion kilometers (1.7 billion miles), and it completes one orbit every 84 years. The length of a day on Uranus as measured by *Voyager 2* is 17 hours, 14 minutes. Uranus is unique among the planets in that its axial tilt is about 90°, meaning that its axis is roughly parallel, not perpendicular to the plane of the ecliptic. This extremely large tilt of its axis is thought to be the result of a collision between the accumulating planet Uranus with another planet-sized body early in the history of the Solar System. Given the unusual orientation of its axis, with the polar regions of Uranus exposed for periods of many years to either continuous sunlight or darkness, planetary scientists were not at all sure what to expect when observing Uranus.

Voyager 2 found that one of the most striking effects of the sideways orientation of Uranus is the effect on the tail of the planetary magnetic field. This is itself tilted about 60 degrees from the Uranian axis of rotation. The planet's magneto tail was shown to be twisted by the rotation of Uranus into a long corkscrew shape following the planet. The presence of a significant magnetic field for Uranus was not at all known until *Voyager's 2* arrival.

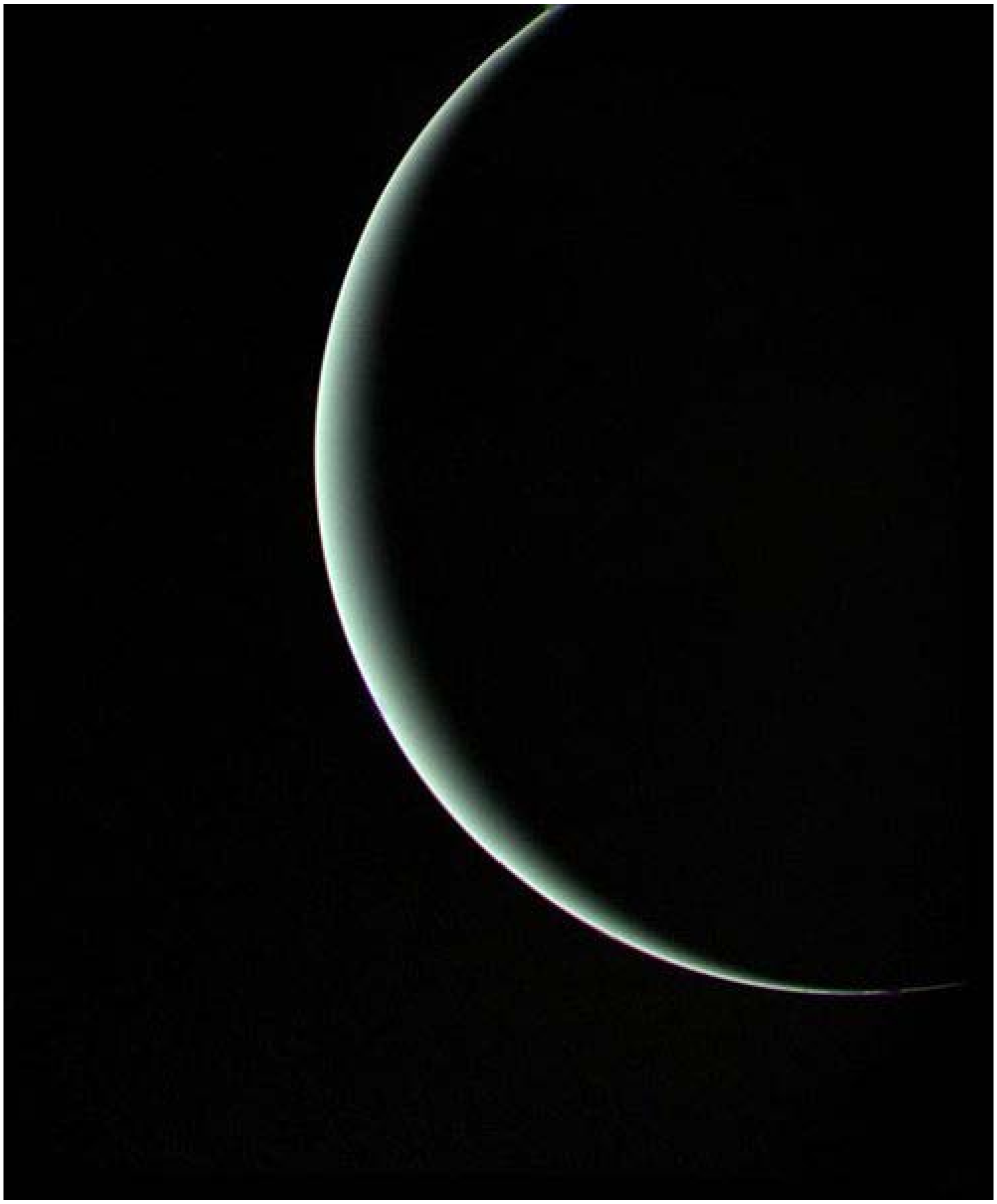
The radiation belts of Uranus were found to be of an intensity similar to those of Saturn. The intensity of radiation within the Uranian belts is such that irradiation would "quickly" darken—within 100,000 years—any methane that is trapped in the icy surfaces of the inner moons and ring particles. This kind of darkening might have contributed to the darkened surfaces of the moons and the ring particles, which are almost uniformly dark gray in color.

A high layer of haze was detected around the sunlit pole of Uranus. This area was also found to radiate large amounts of ultraviolet light, a phenomenon that is called "dayglow." The average atmospheric temperature is about 60 K (−350 degrees Fahrenheit/−213 degrees Celsius). Surprisingly, the illuminated and dark poles, and most of the planet, exhibit nearly the same temperatures at the cloud tops.

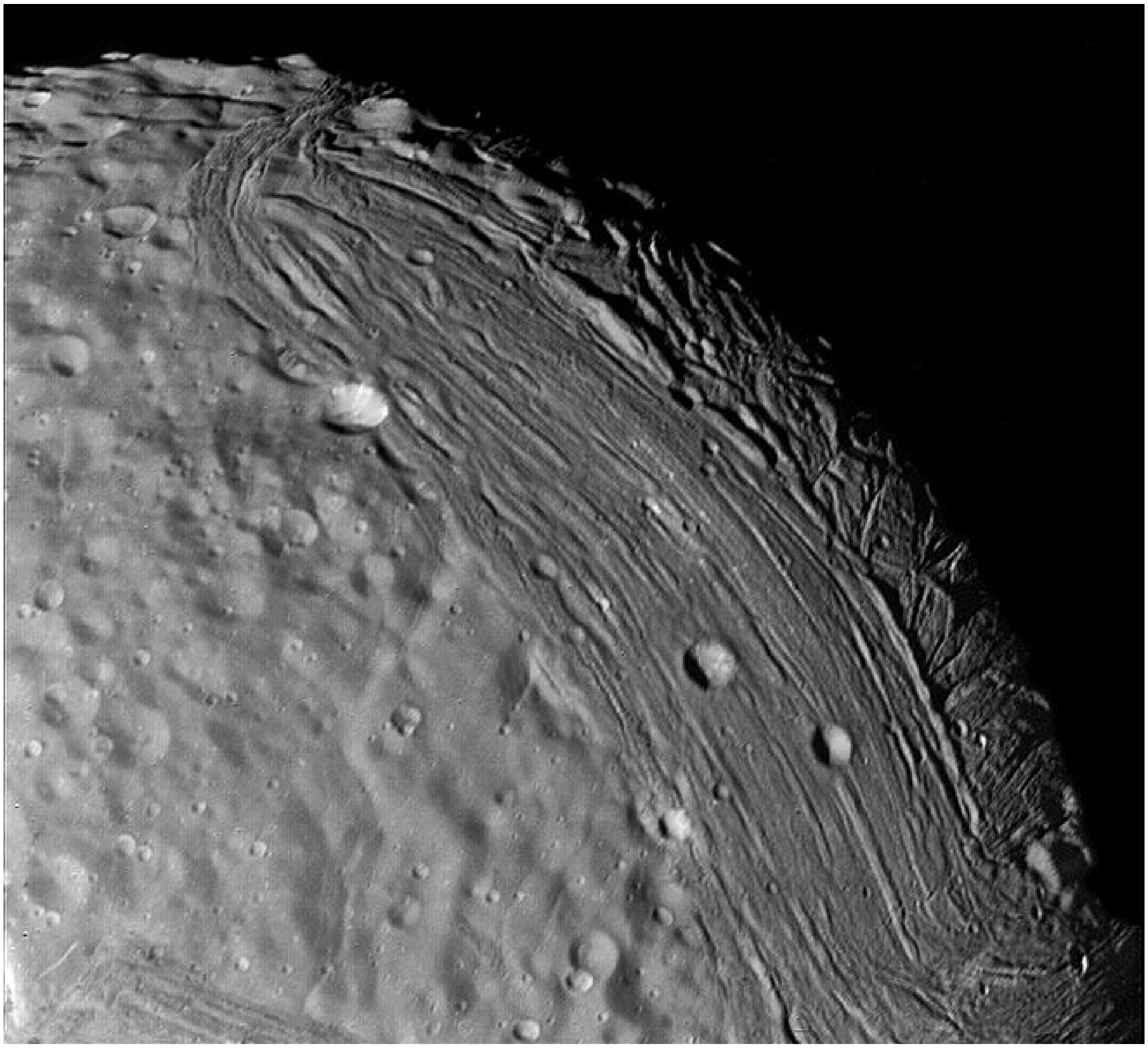
The Uranian moon Miranda, the innermost of the five large moons, was discovered to be one of the strangest bodies yet seen in the Solar System. Detailed images from *Voyager 2's* flyby of Miranda showed huge canyons made from geological faults as deep as 20 kilometers (12 miles), terraced layers, and a mixture of old and young surfaces. One hypothesis suggests that Miranda might consist of a reaggregation of material following an earlier event when Miranda was shattered into pieces by a violent impact.

All nine of the previously known Uranian rings were studied by the instruments of *Voyager 2*. These measurements showed that the Uranian rings are distinctly different from those at Jupiter and Saturn. The Uranian ring system might be relatively young, and it did not form at the same time that Uranus did. The particles that make up the rings might be the remnants of a moon that was broken up by either a high-velocity impact or torn up by tidal effects.

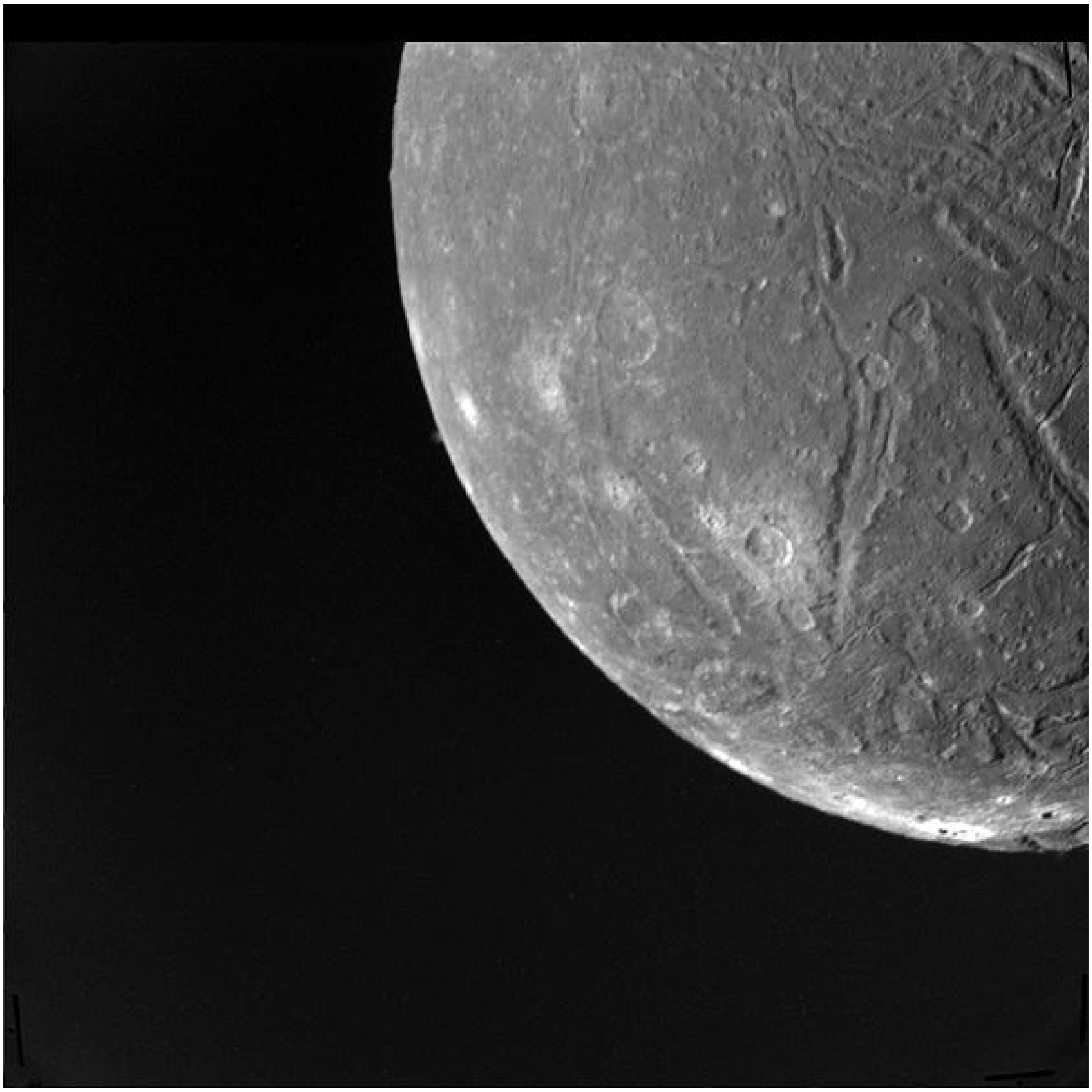
Uranus viewed from 18 million km.



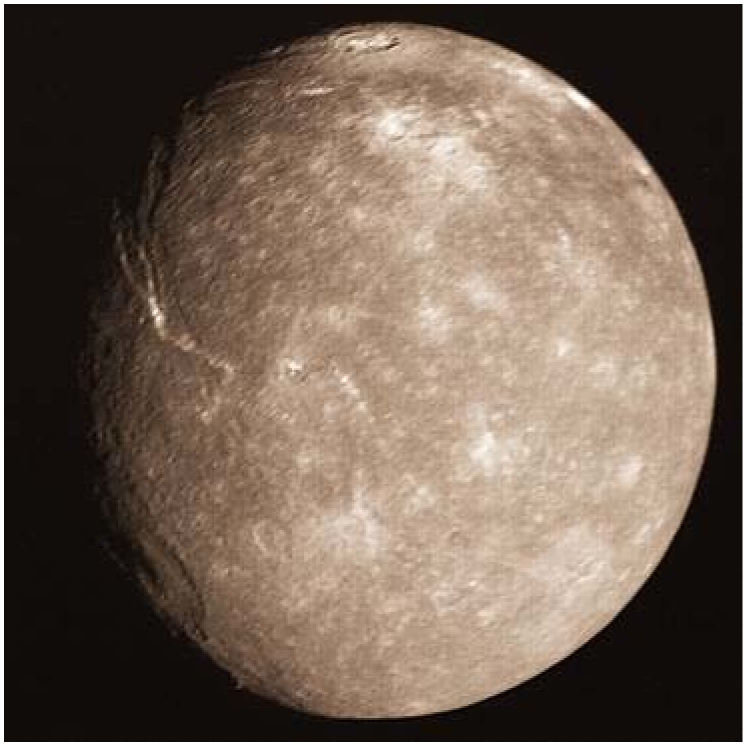
Departing image of crescent Uranus.

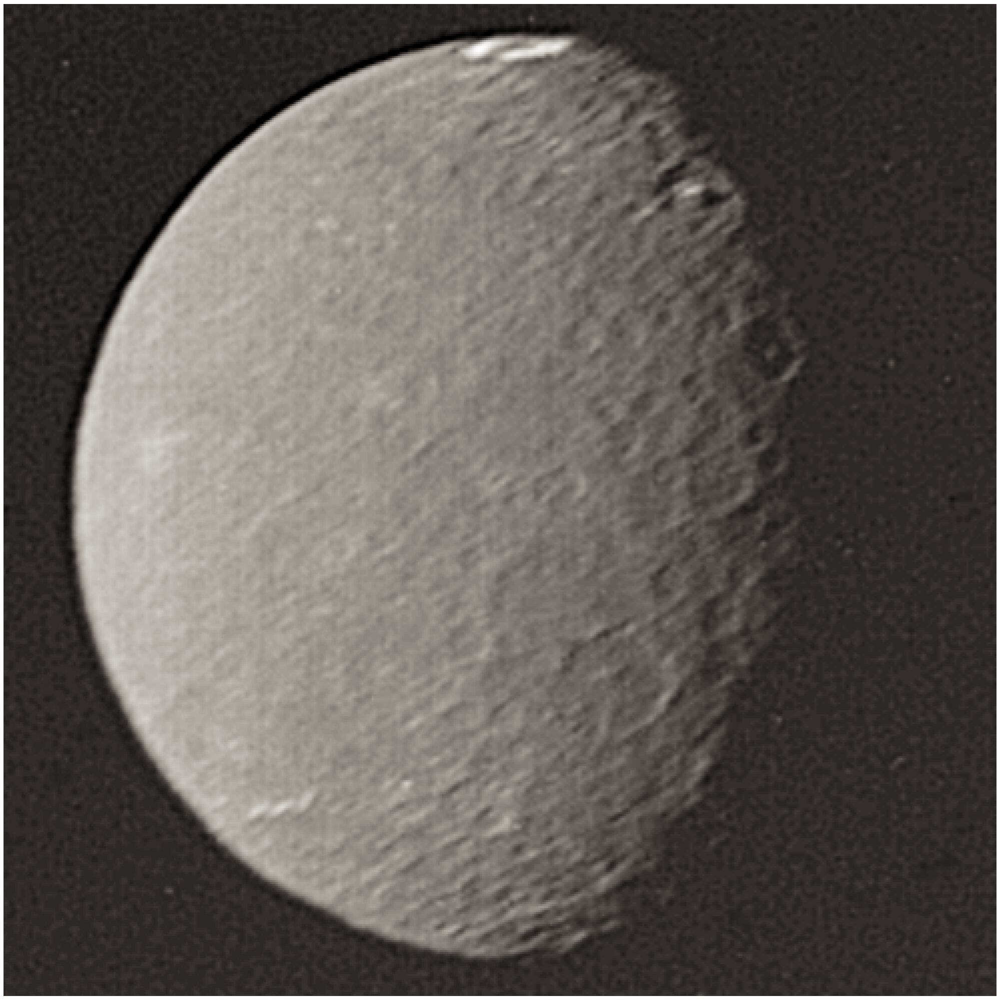


Fractured surface of Miranda.

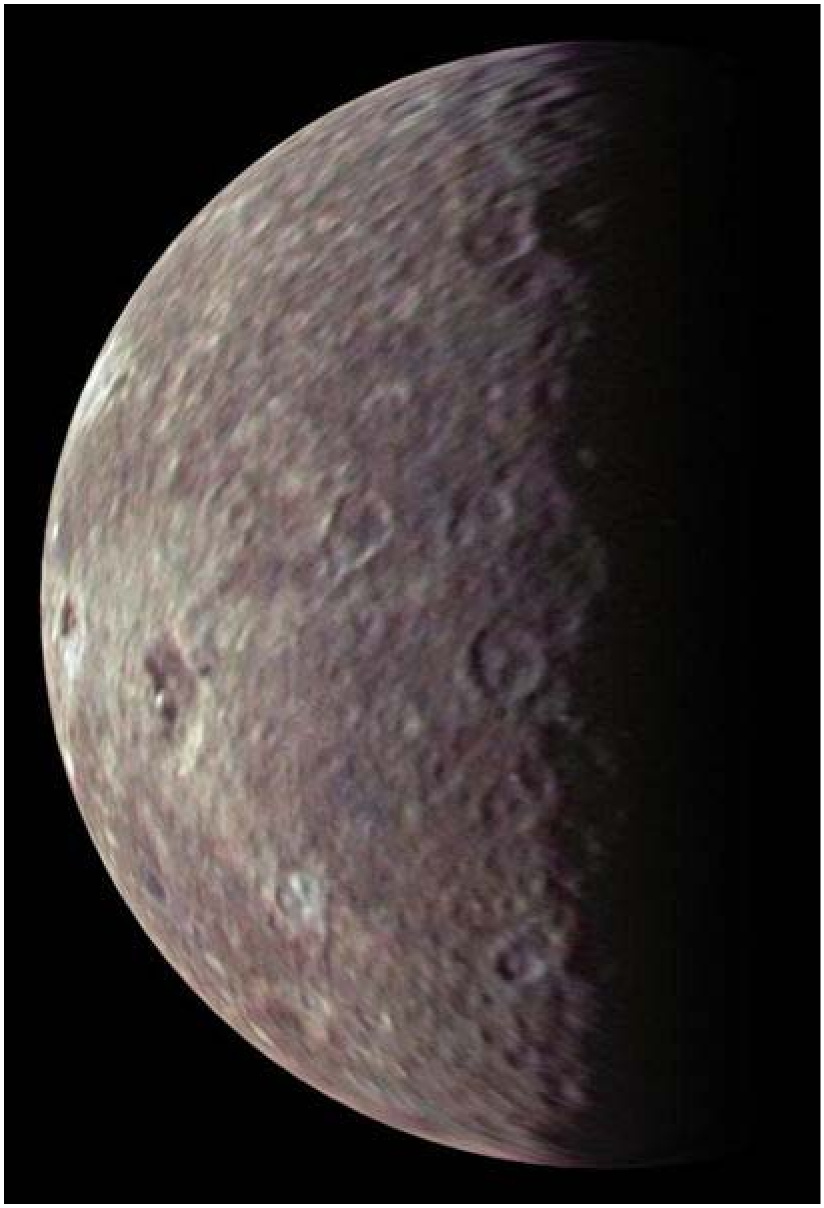


Ariel as imaged from 130,000 km.


Color composite of Titania from 500,000 km.



Umbriel (moon) imaged from 550,000 km.



Color composite of Oberon.

The Rings of Uranus imaged by *Voyager 2*.

Encounter with Neptune

Voyager 2's closest approach to Neptune occurred on August 25, 1989. Since this was the last planet of our Solar System that *Voyager 2* could visit, the Chief Project Scientist, his staff members, and the flight controllers decided to also perform a close fly-by of Triton, the larger of Neptune's two originally known moons, so as to gather as much information on Neptune and Triton as possible, regardless of what angle at which Voyager 2 would fly away from Neptune. This was just like the case of *Voyager 1's* encounters with Saturn and its massive moon Titan.

Through repeated computerized test simulations of trajectories through the Neptunian system conducted in advance, flight controllers determined the best way to route *Voyager*

2 through the Neptune-Triton system. Since the plane of the orbit of Triton is tilted significantly with respect to the plane of the ecliptic, through mid-course corrections, *Voyager 2* was directed into a path several thousand miles over the north pole of Neptune. At that time, Triton was behind and below (south of) Neptune (at an angle of about 25 degrees below the Ecliptic), close to the apoapsis of its elliptical orbit. The gravitational pull of Neptune bent the trajectory of *Voyager 2* down in the direction of Triton. In less than 24 hours, *Voyager 2* traversed the distance between Neptune and Triton, and then it observed the northern hemisphere of Triton as *Voyager 2* passed over the north pole of Triton.

The net and final effect on the trajectory of *Voyager 2* was to bend its trajectory south below the plane of the Ecliptic by about 30 degrees. *Voyager 2* is on this path permanently, and hence, it is exploring space south of the plane of the Ecliptic, measuring magnetic fields, charged particles, etc., there, and sending the measurements back to the Earth via telemetry.

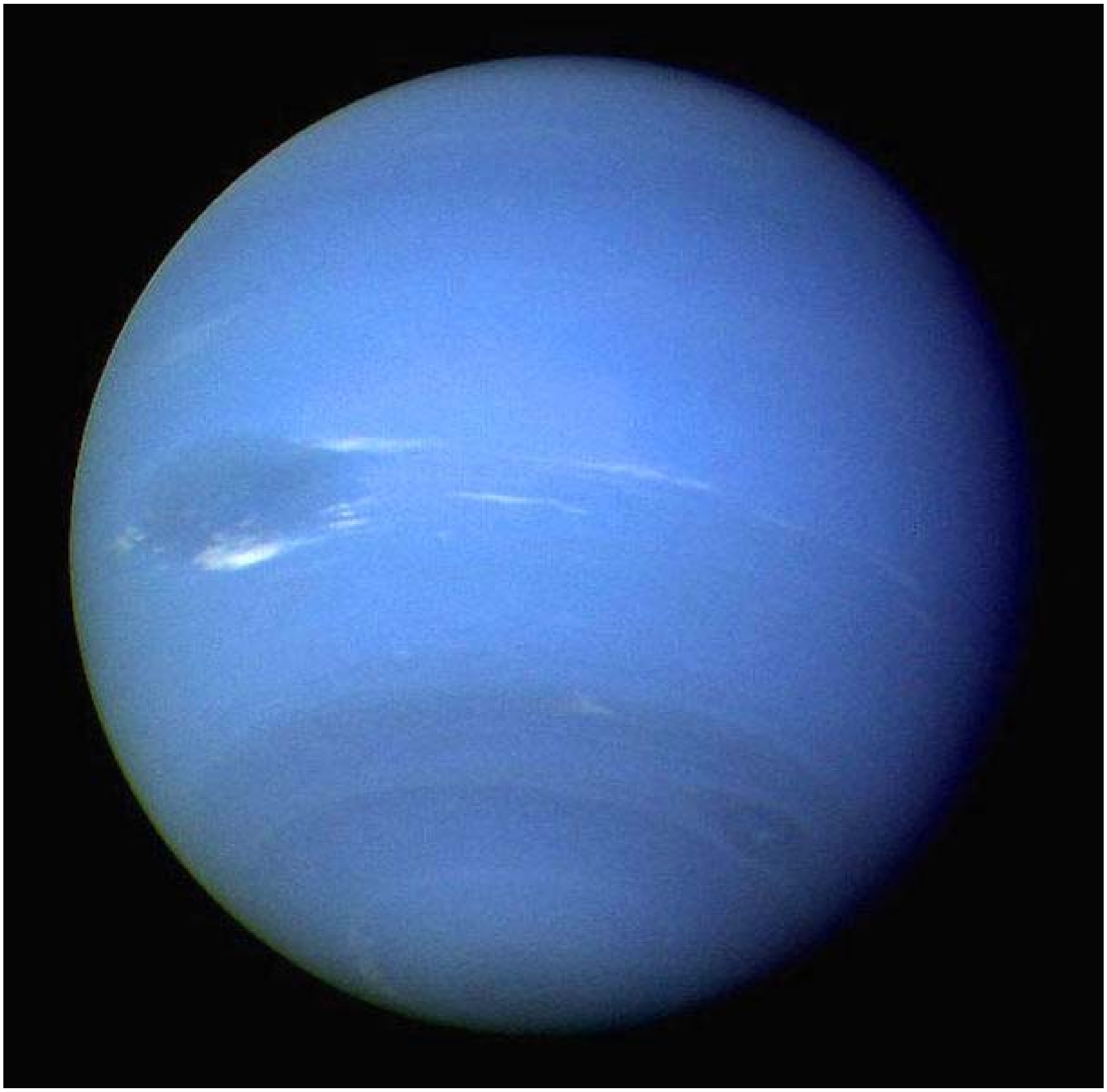
While in the neighborhood of Neptune, *Voyager 2* discovered the "Great Dark Spot", which has since disappeared, according to observations by the Hubble Space Telescope. Originally thought to be a large cloud itself, the "Great Dark Spot" was later hypothesized to be a hole in the visible cloud deck of Neptune.

Neptune's atmosphere consists of hydrogen, helium, and methane. The methane in Neptune's upper atmosphere absorbs the red light from the Sun, but it reflects the blue light from the sun back into space. This is why Neptune looks blue.

For decades, beginning in the late 19th century, it was widely thought that an unseen planet (dubbed "Planet X") was influencing the orbits of Uranus and Neptune, by perturbing them, since their observed positions differed somewhat from the positions predicted by calculations. This notion might have brought about the 1930 discovery of Pluto, but the actual discovery of Pluto by Clyde Tombaugh in 1930 was an accidental one that occurred while a few astronomers were scanning areas of the sky for "Planet X".

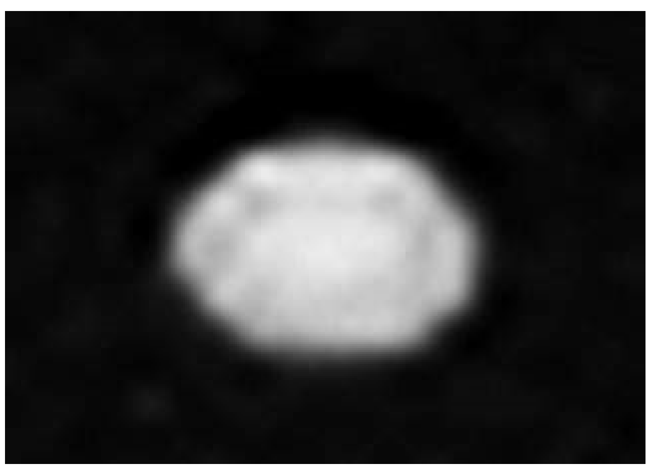
The notion of a "Planet X" has persisted, because over the decades since 1930, it became increasingly clear that Pluto has insufficient mass to account for the observational discrepancies. When *Voyager 2* flew-by Neptune, it took very precise measurements of Neptune's mass. Neptune was evaluated at about 0.5 percent less massive than previous estimates — a difference comparable to a planet with the mass of Mars. When the orbits of Uranus and Neptune orbits were recalculated using the more accurate mass figure, it was found that the imprecise number for Neptune — and not the gravity of an unseen planet — caused the orbital discrepancies that had long perplexed planetary astronomers.

With the decision of the International Astronomical Union to reclassify Pluto as a "plutoid" in 2008, the flyby of Neptune by *Voyager 2* in 1989 became the point when every known planet in the Solar System had been visited at least once by a space probe.

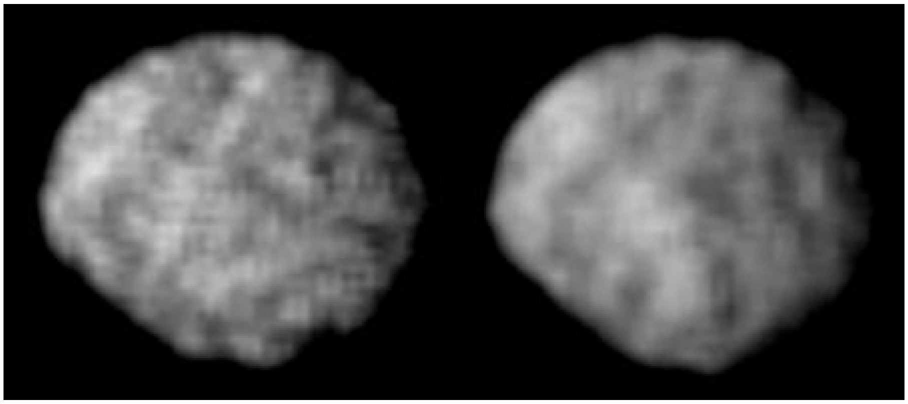


Voyager 2 image of Neptune.

Neptune and Triton three days after *Voyager 2* flyby.



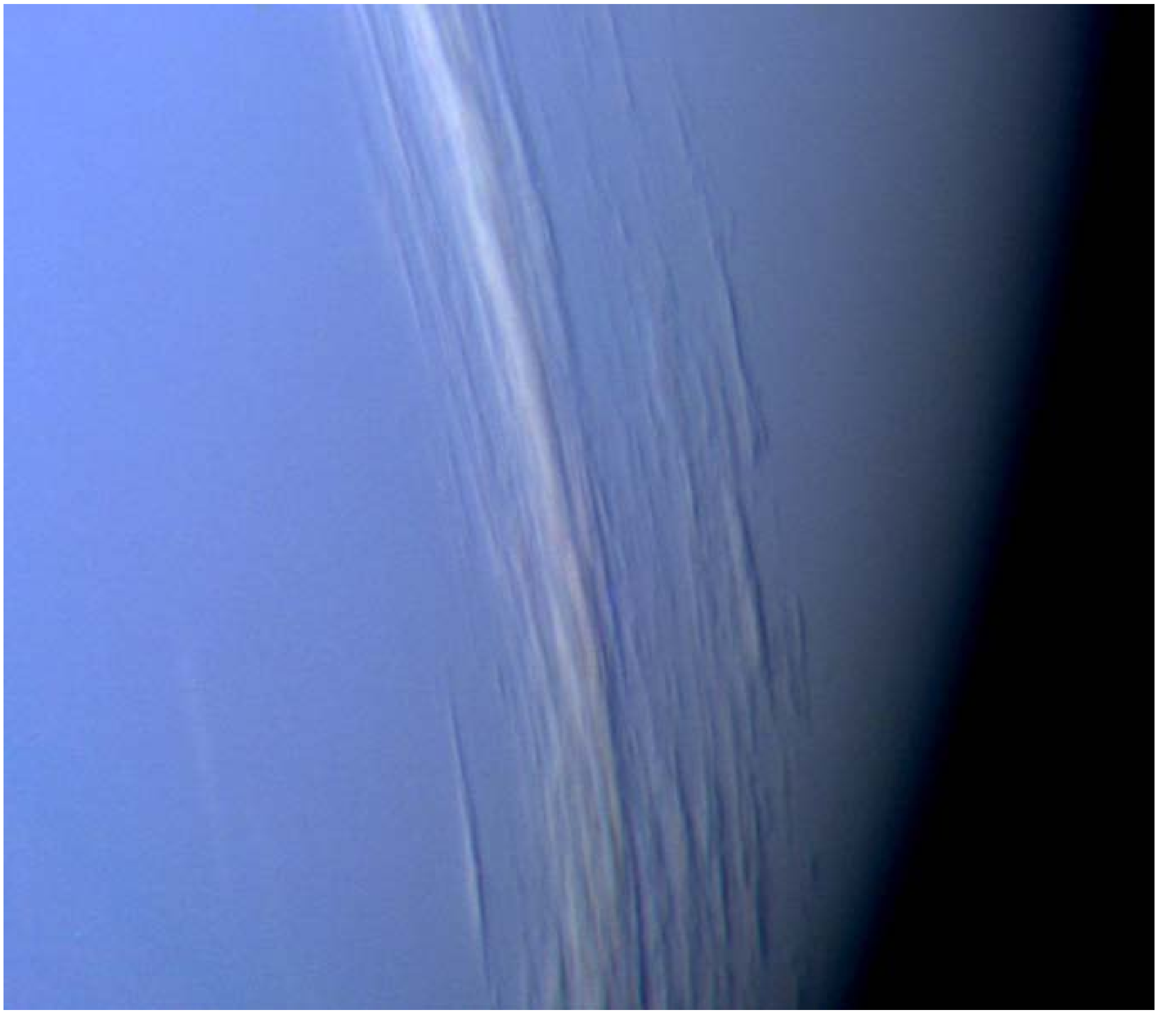
Despina as imaged from *Voyager 2*.

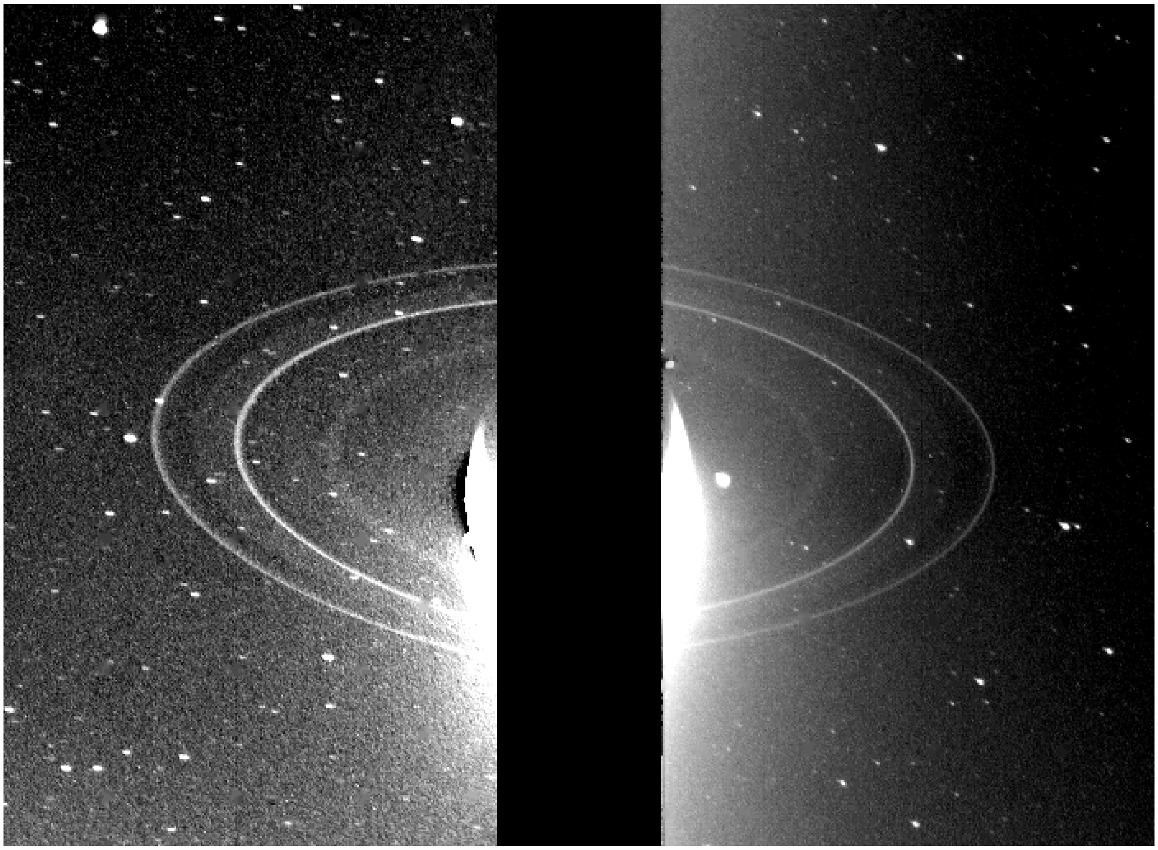


Cratered surface of Larissa.

Dark surface of Proteus.

Color mosaic of *Voyager 2* Triton.


Cirrus clouds imaged above gaseous Neptune.



Rings of Neptune taken in occultation from 280,000 km.

Interstellar mission

Since its planetary mission is over, *Voyager 2* is now described as working on an interstellar mission, which NASA is using to find out what the solar system is like beyond the heliosphere. On August 30, 2007, *Voyager 2* passed the termination shock into the heliosheath, approximately 1 billion miles (1.6 billion km) closer to the Sun than *Voyager 1* did. This is due to the local interstellar magnetic field of deep space. The southern hemisphere of the solar system's heliosphere is being pushed in.

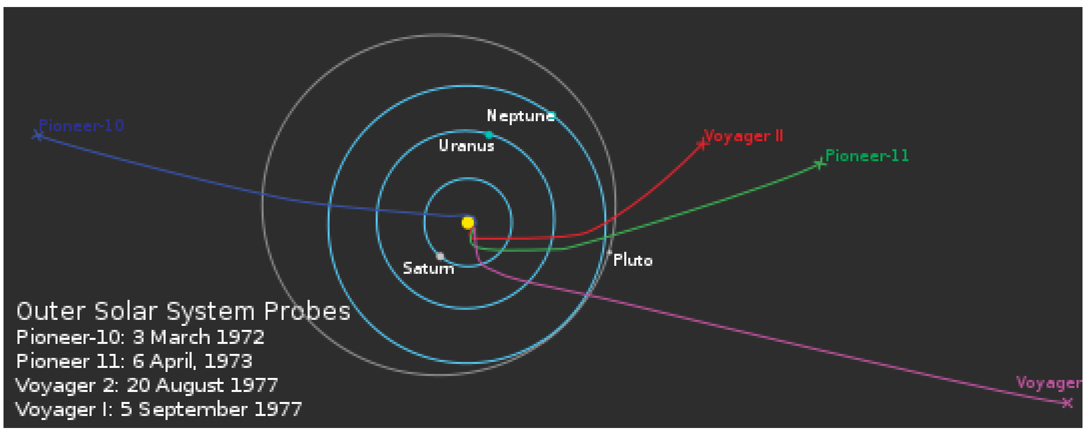
As of April 13, 2010, *Voyager 2* was at a distance of around 91.898 AU (13.747 billion km, 8.542 billion miles or 0.001443 light years) from the Sun, deep in the scattered disc, and traveling outward at roughly 3.264 AU per year. It is more than twice as far from the Sun as Pluto, and far beyond the perihelion of 90377 Sedna, but not yet beyond the outer limits of the orbit of the dwarf planet Eris.

Voyager 2 is not headed toward any particular star. If left alone, it should pass by star Sirius, which is currently about 2.6 parsecs from the Sun and moving diagonally towards the Sun, at a distance of 1.32 parsecs (4.3 ly, 25 trillion mi) in about 296,000 years.

Voyager 2 is expected to keep transmitting weak radio messages until at least 2025, over 48 years since it was launched.

Year	End of specific capabilities as a result of the available electrical power limitations
1998	Terminate scan platform and UV observations
2007	Termination of *Digital Tape Recorder* (DTR) operations (It was no longer needed due to a failure on the *High Waveform Receiver* on the *Plasma Wave Subsystem* (PWS) on June 30, 2002.)
2008	Power off *Planetary Radio Astronomy Experiment* (PRA)
2015 approx	Termination of gyroscopic operations
2020 approx	Initiate instrument power sharing
2025 or slightly afterwards	Can no longer power any single instrument

Current status



Location and trajectories of Pioneer and Voyager spacecraft, as of July 7, 2007. Note Voyager 2 is further than Pioneer 11 and only appears closer here due to its -55 degree declination, and that Voyager 1's position is drawn too far away.

Voyager 2 is currently transmitting scientific data at about 160 bits per second. Information about continuing telemetry exchanges with *Voyager 2* is available from Voyager Weekly Reports. Information on the current location of *Voyager 2* can be found at HeavensAbove.

As of August 2010, *Voyager 2* is 93 AU from the Sun, at −55.32° declination and 19.785 h right ascension, placing it in the constellation Telescopium as observed from Earth.

On November 30, 2006, a telemetered command to *Voyager 2* was incorrectly decoded by its on-board computer—in a random error—as a command to turn on the electrical heaters of the spacecraft's magnetometer. These heaters remained turned on until December 4, 2006, and during that time, there was a resulting high temperature above 130 °C (266 °F), significantly higher than the magnetometers were designed to endure, and a sensor rotated away from the correct orientation. It has not been possible to fully diagnose and correct for the damage caused to the *Voyager 2's* magnetometer, although efforts to do so are proceeding.

There are regular posts of the current distance of *Voyager 2* to Earth in light-travel time to Twitter.

On April 22, 2010, *Voyager 2* encountered scientific data format problems as reported by the Associated Press on May 7, 2010.

On May 17, 2010, JPL engineers revealed that a flipped bit in an on-board computer had caused the issue, and scheduled a bit reset for May 19.

On May 23, 2010, *Voyager 2* has resumed sending science data from deep space after engineers fixed the flipped bit.

Currently research is being made into making the area of memory with the flipped bit off limits or disallowing its use.

The Low-Energy Charged Particle Instrument is currently operational and data from this instrument concerning charged particles is being transmitted to Earth. This data permits measurements of the heliosheath and termination shock.

Chapter- 5

Galileo (Spacecraft)

***Galileo* Orbiter**

Galileo is prepared for mating with the IUS booster

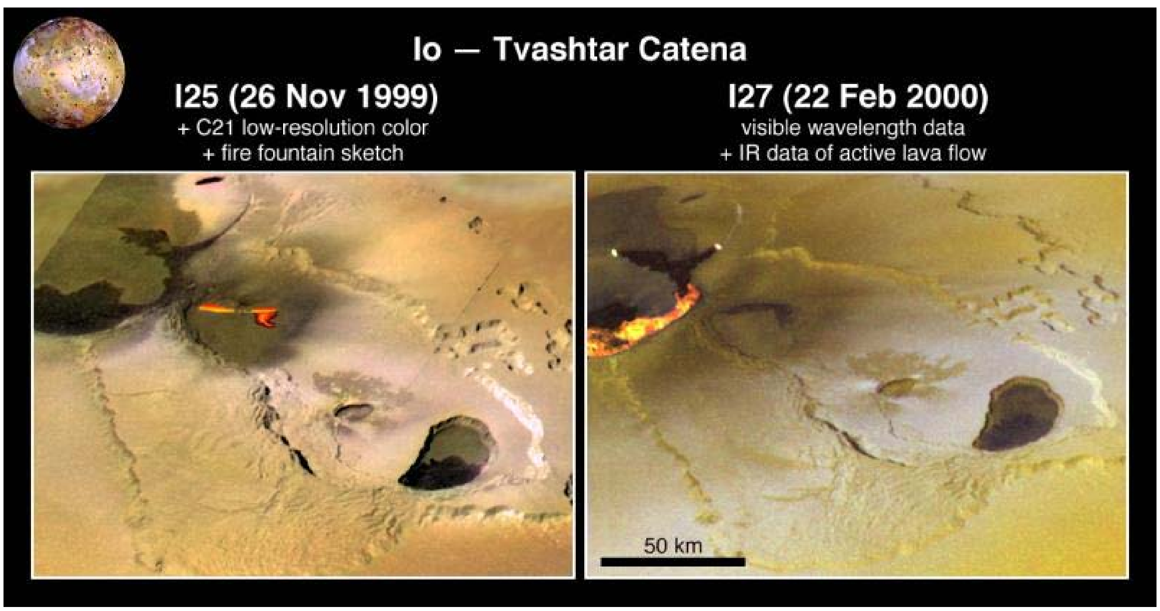
Operator	NASA
Mission type	Orbiter, Fly-by
Flyby of	Venus, Earth, 951 Gaspra, 243 Ida
Satellite of	**Jupiter**
Orbital insertion date	1995-12-08 01:20:00 UTC

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.

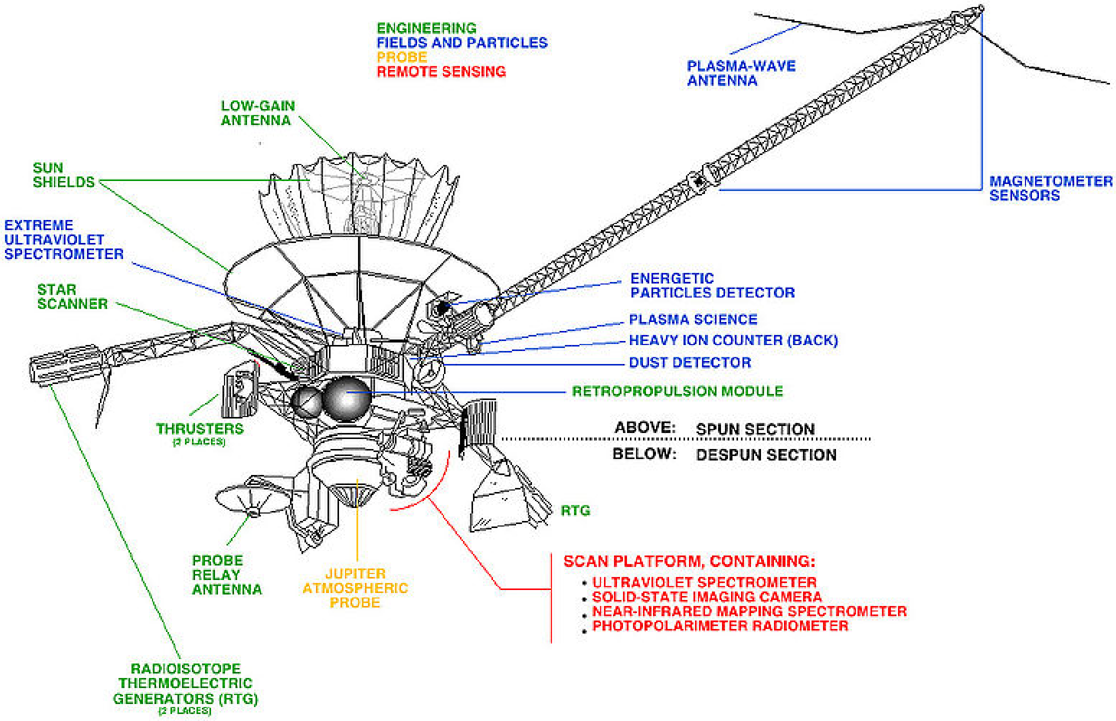
Propulsion

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 ft^2) 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

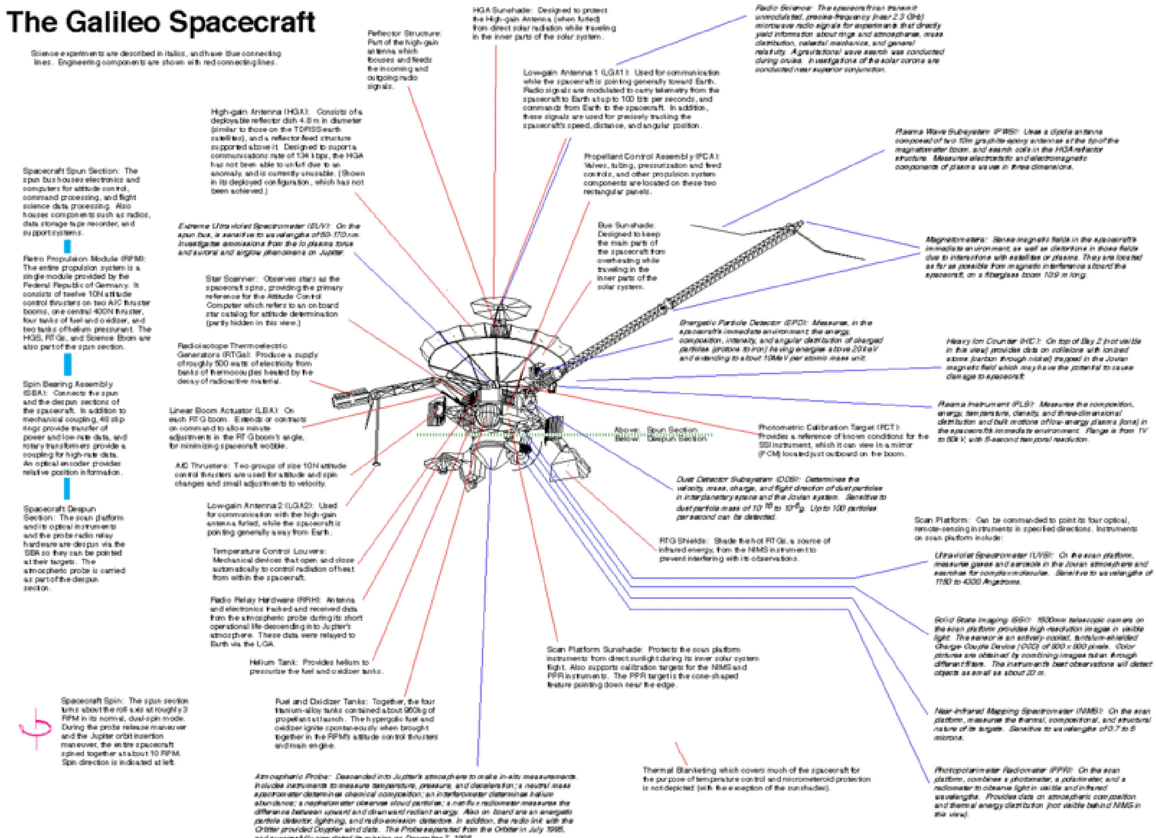
Scientific instruments to measure fields and particles were mounted on the spinning section of the spacecraft, together with the main antenna, power supply, the propulsion module and most of the *Galileo* computers and control electronics. The sixteen instruments, weighing 118 kg altogether, included 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



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.

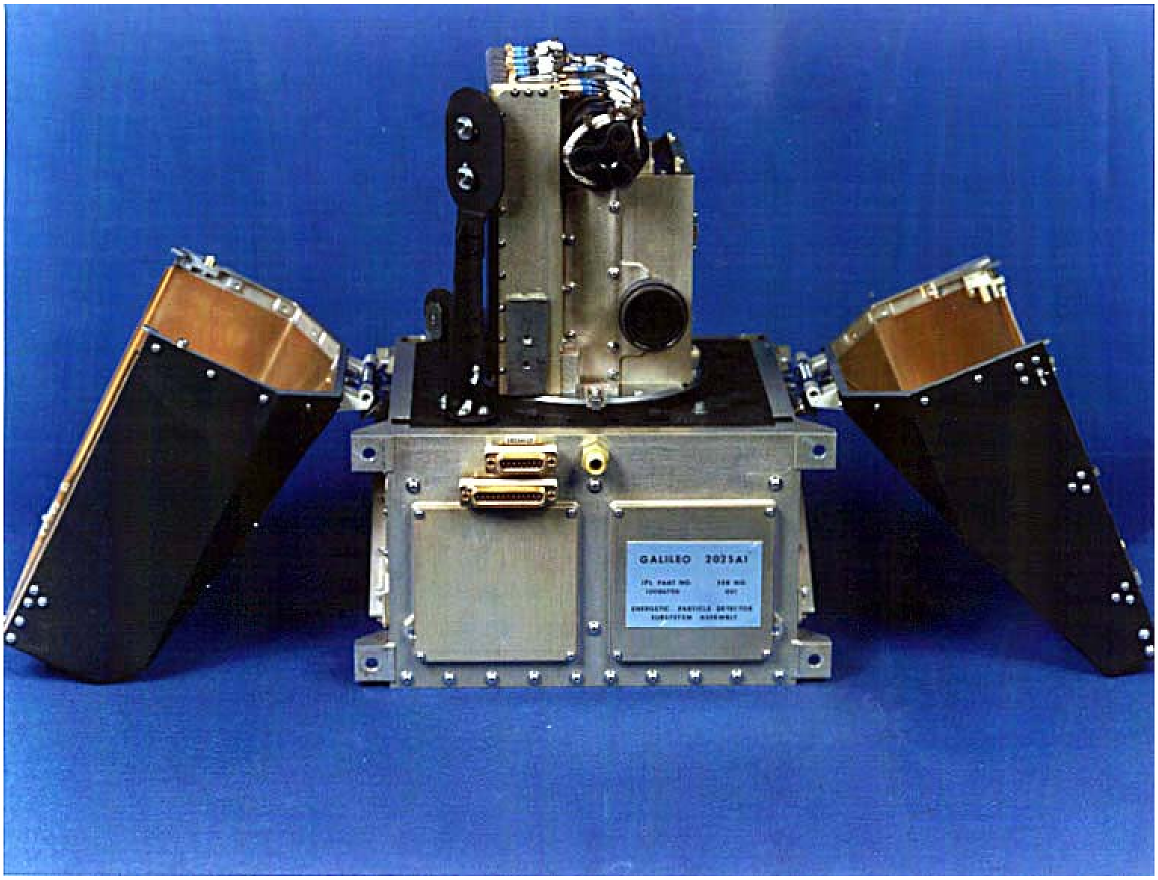
Ultraviolet Spectrometer / Extreme Ultraviolet Spectrometer (UVS/EUV)

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.

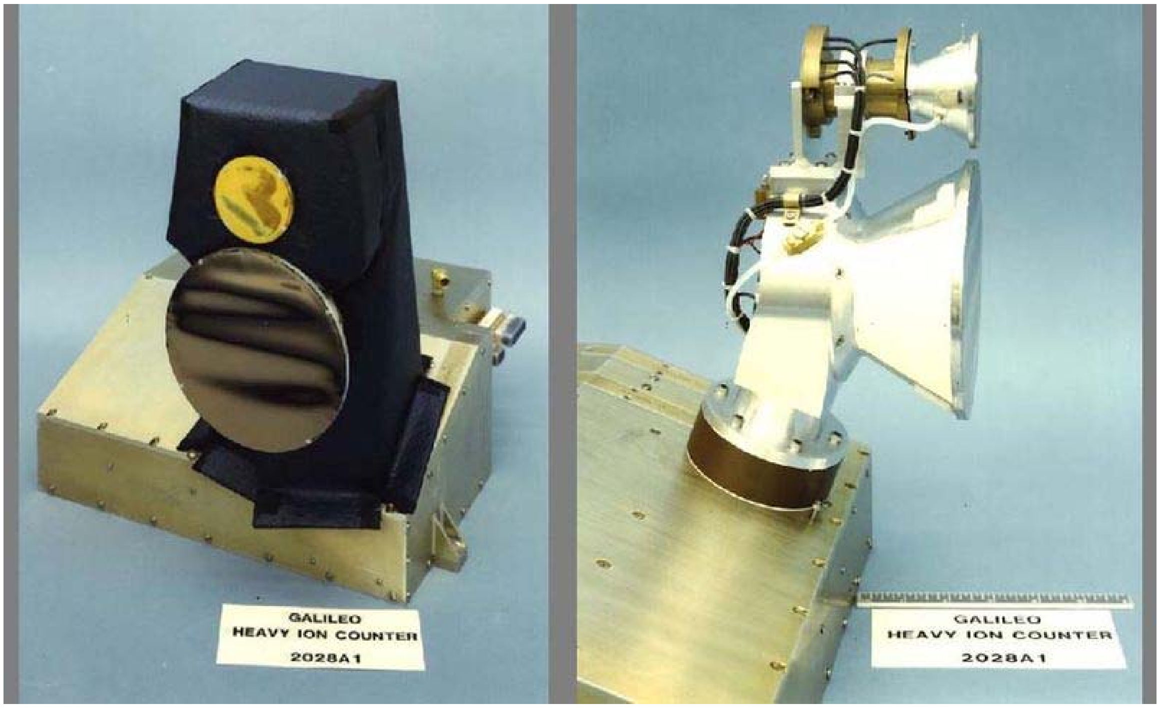
Photopolarimeter-Radiometer (PPR)

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)

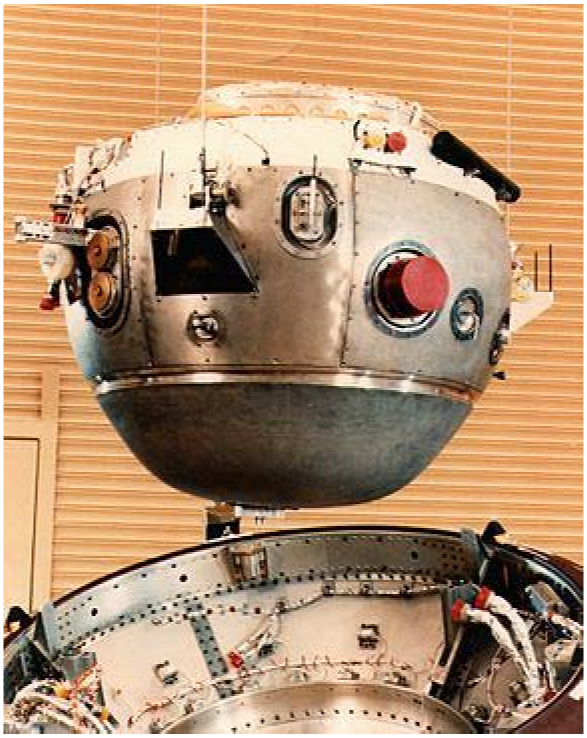
The PLS uses seven fields of view to collect charged particles for energy and mass analysis. These fields of view cover most angles from 0 to 180 degrees, fanning out from the spin axis. The rotation of the spacecraft carries each field of view through a full circle. The PLS will measure particles in 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

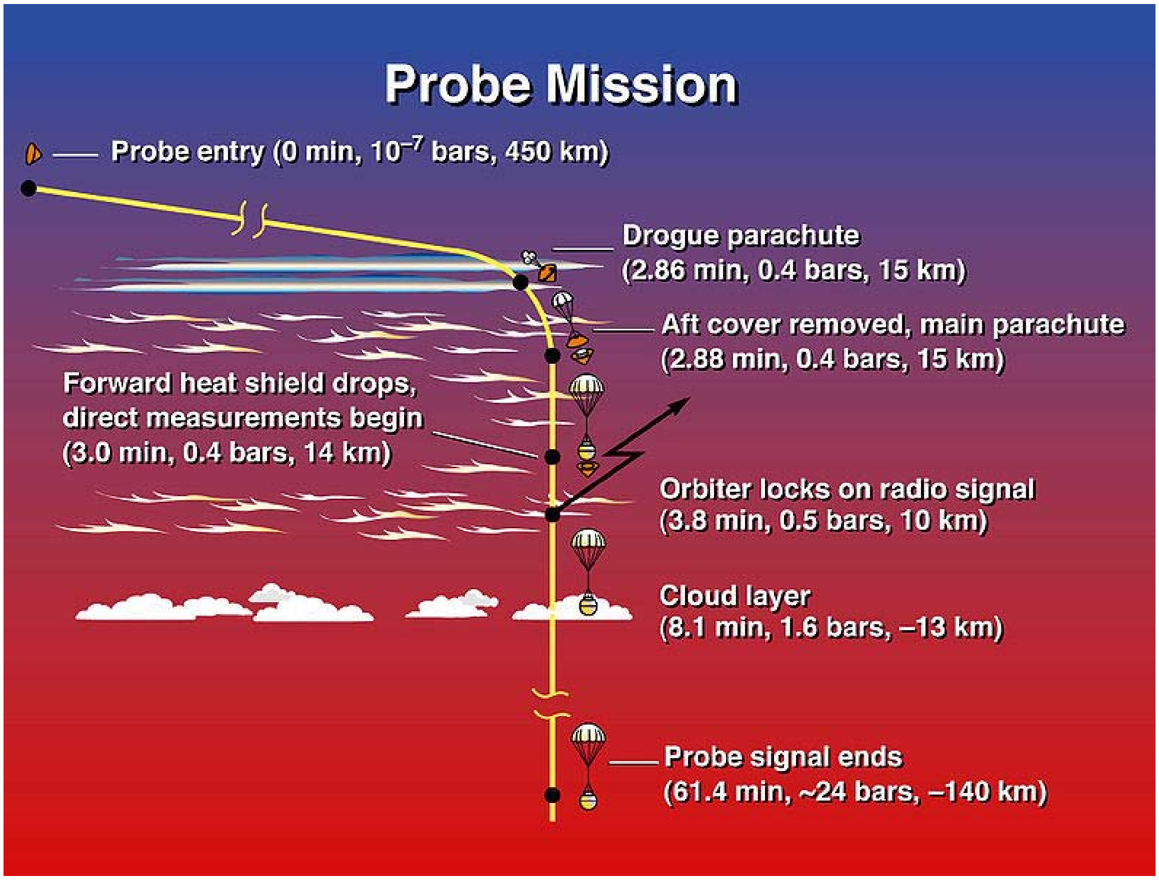
Galileo Probe



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.

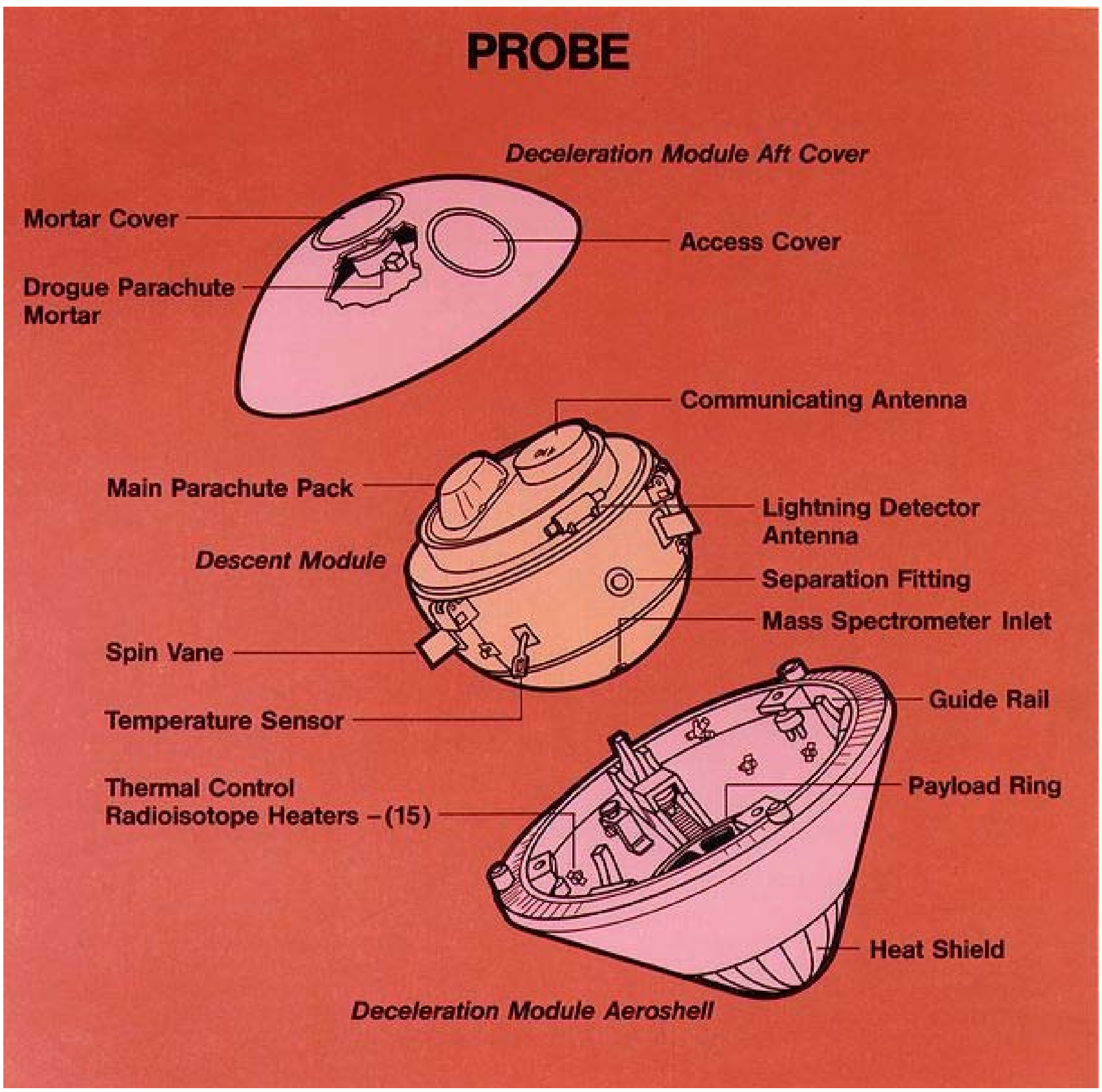


Diagram of *Galileo* atmospheric entry probe instruments and subsystems.

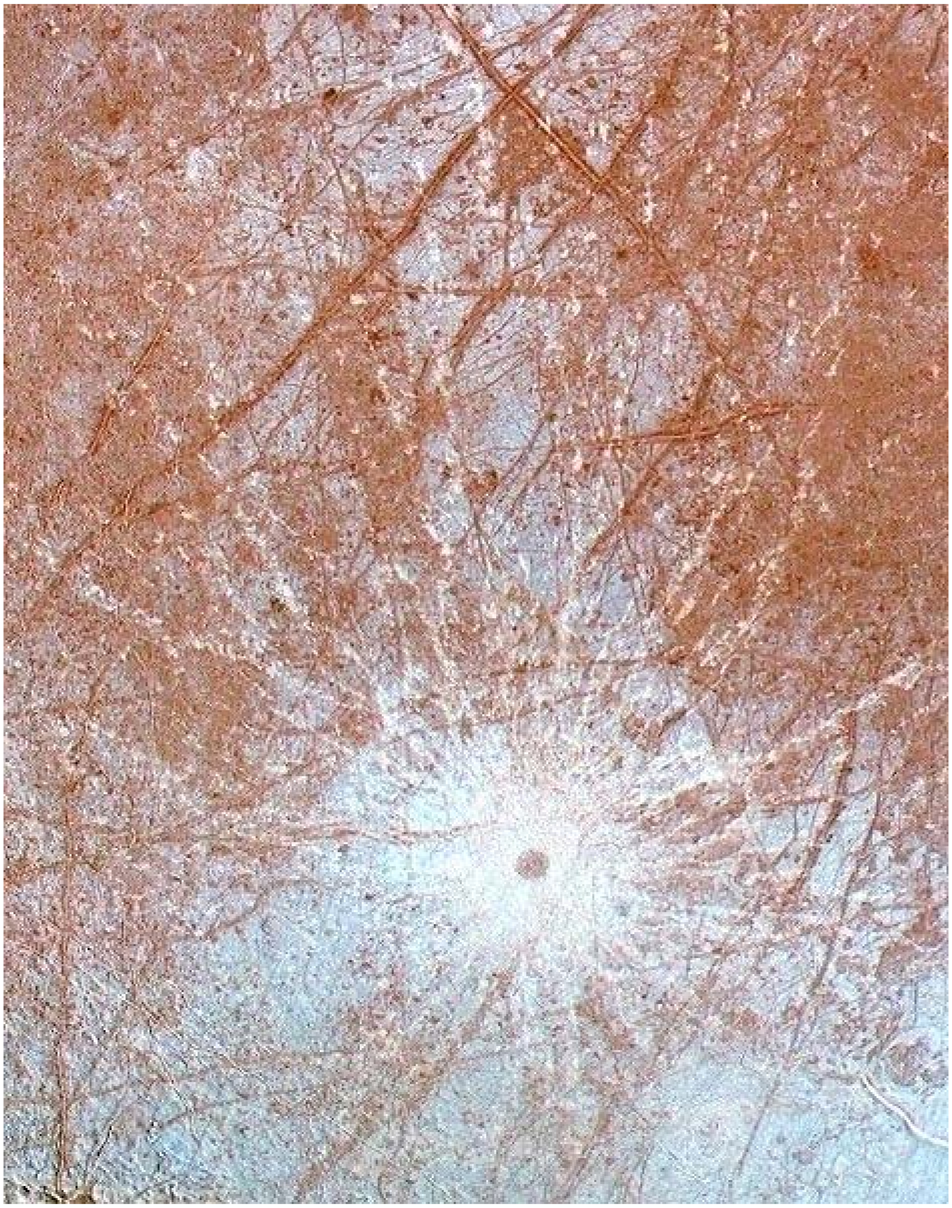
The probe included six instruments for taking data on its plunge into Jupiter:

- 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.

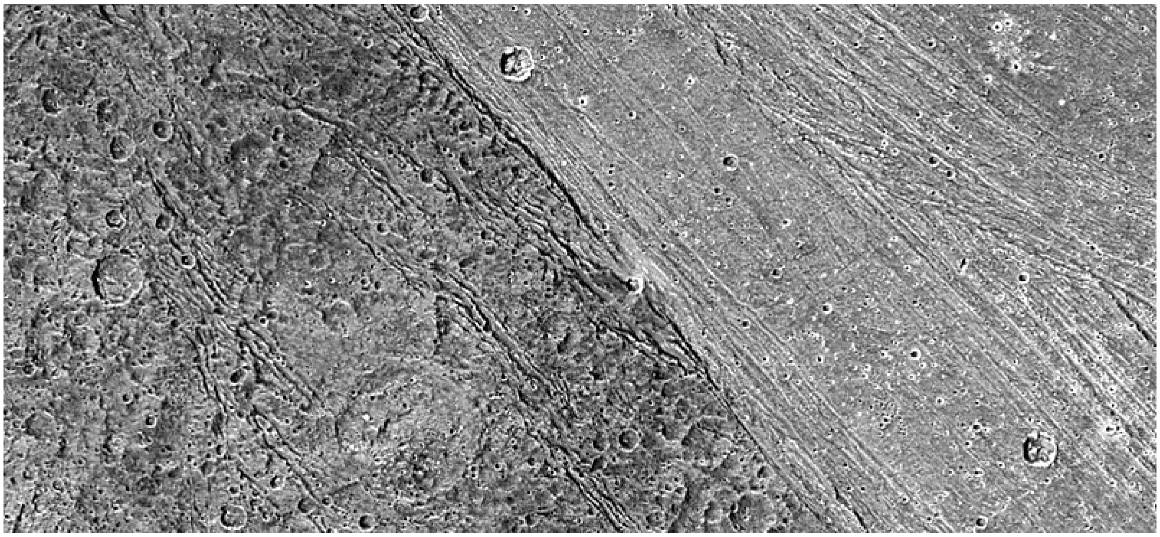
Total data returned from the probe was about 3.5 megabits (~458752 bytes). The probe stopped transmitting before the line of sight link with the orbiter was cut. The likely proximal cause of the final probe failure was overheating, which sensors indicated before signal loss.

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.

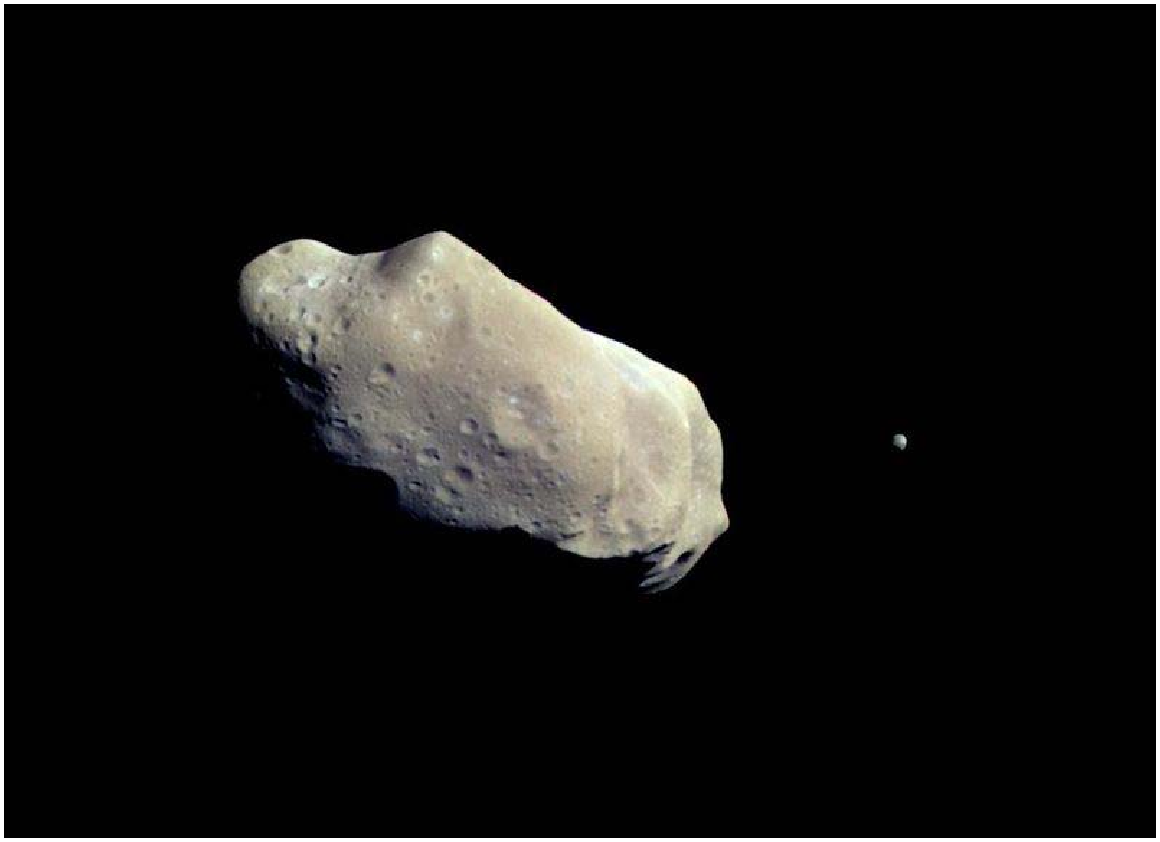
Asteroid encounters

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

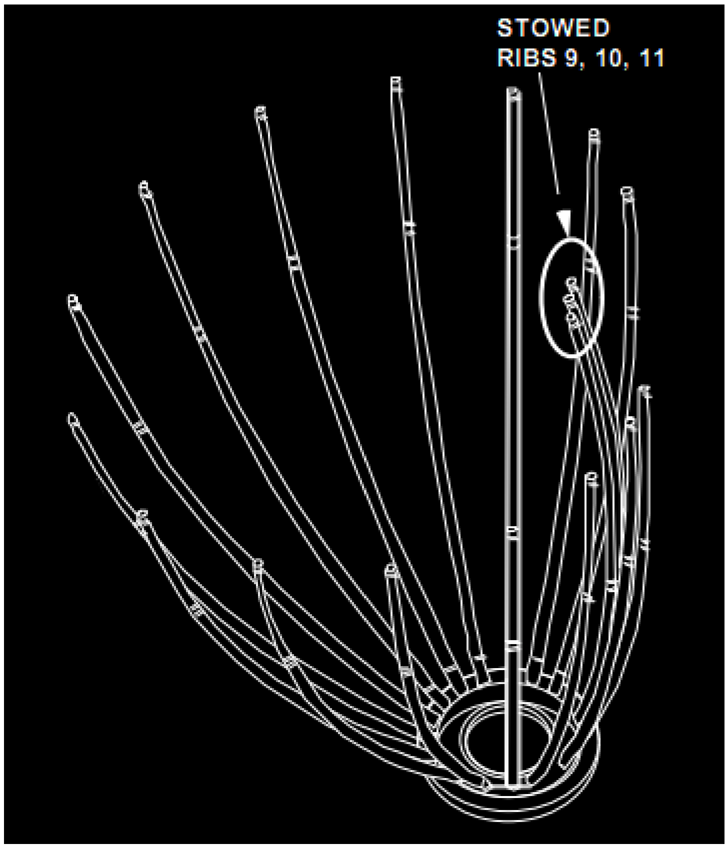


NASA image of 243 Ida. The tiny dot to the right is its moon, Dactyl.

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.

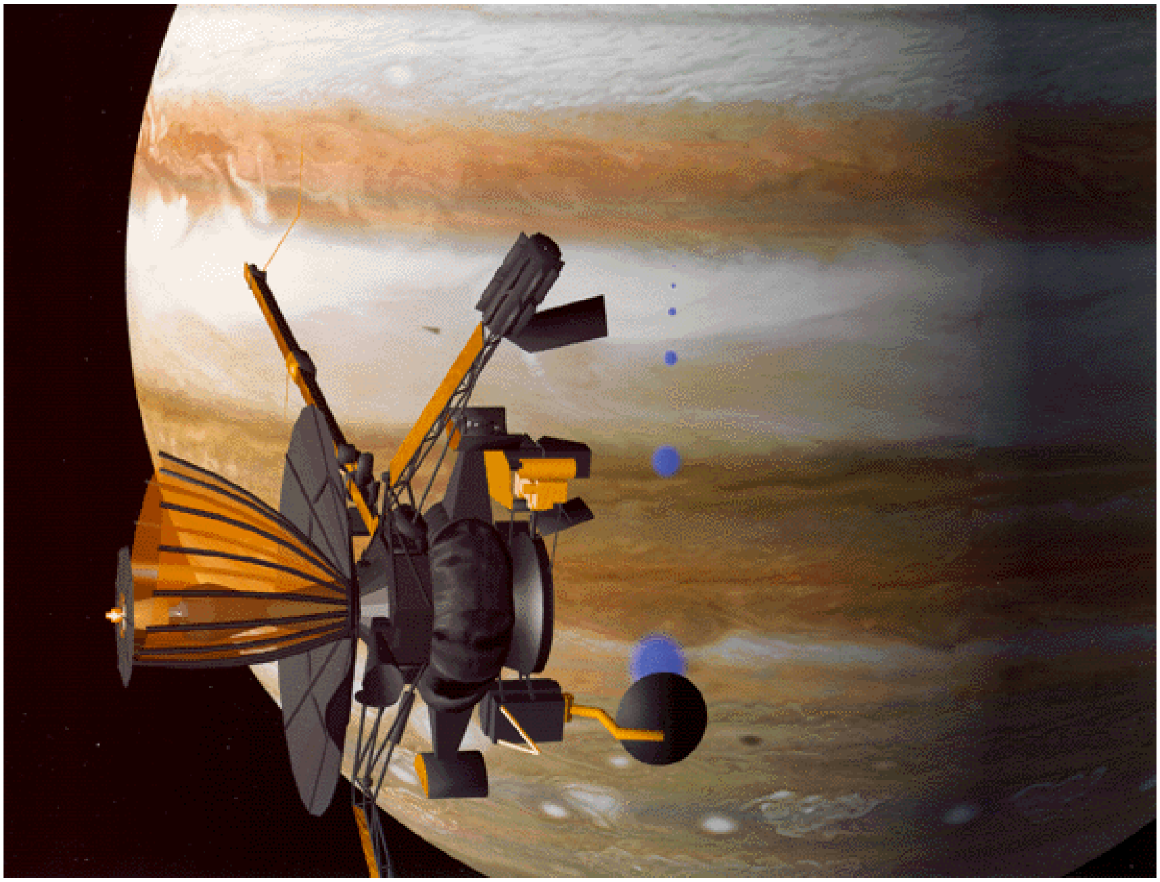
Spacecraft malfunctions

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.