# Spacecraft Missions to Jupiter and Saturn

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# Chapter 1

# Juno (Spacecraft)

**Juno**

An artist's concept of *Juno* at Jupiter

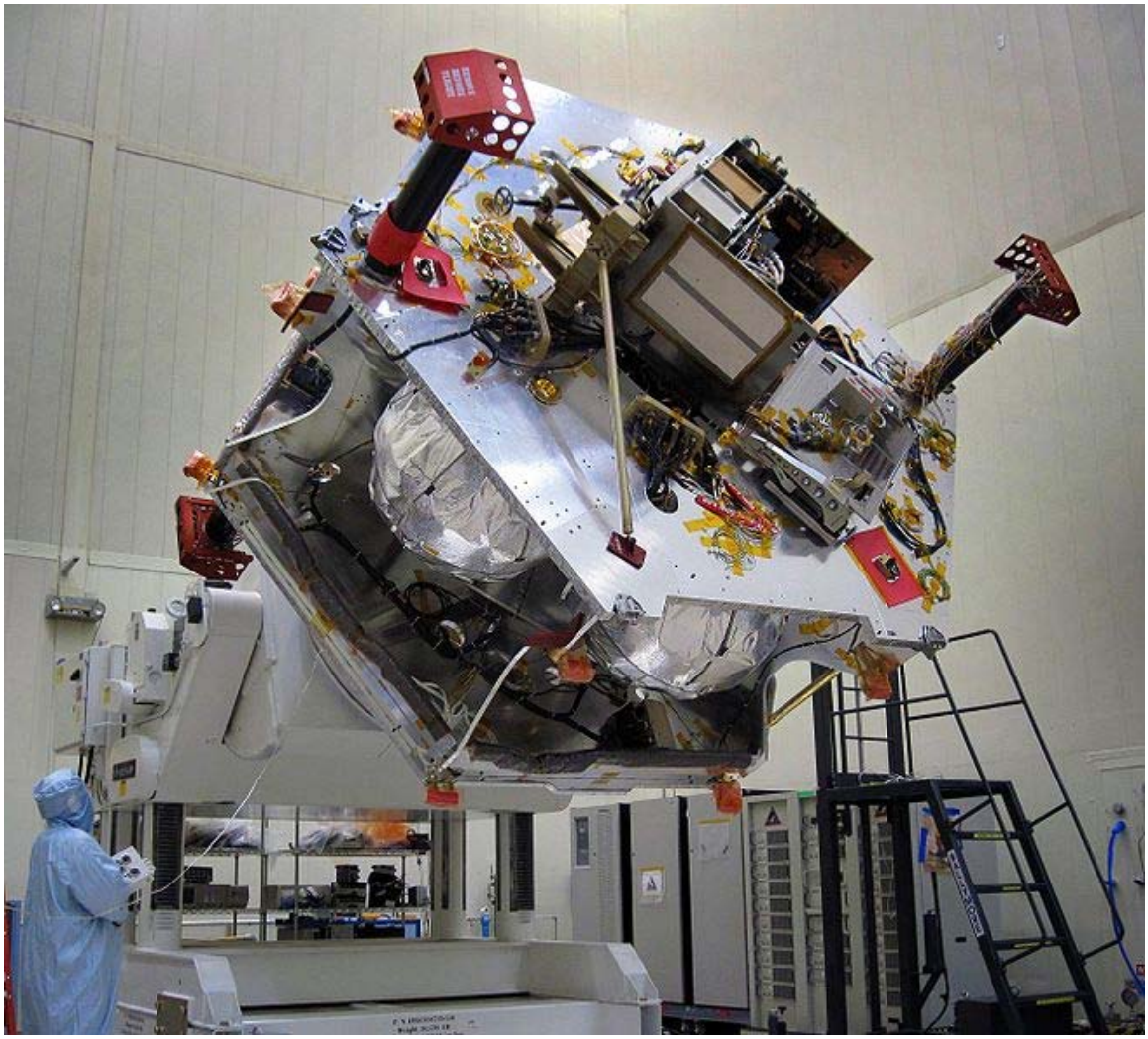
| | |
|---|---|
| **Operator** | NASA |
| **Major contractors** | Lockheed Martin Corporation |
| **Mission type** | Orbiter |
| **Flyby of** | Earth |
| **Satellite of** | **Jupiter** |
| **Orbital insertion date** | 2016 |
| **Orbits** | 32 |
| **Launch date** | August 2011 |

| | |
|---|---|
| **Launch vehicle** | Atlas V 551 |
| **Mission duration** | 1 Earth year |
| **Homepage** | Mission home<br>NASA page |
| **Power** | Solar power |
| **Orbital elements** | |
| **Regime** | Polar |
| **Periapsis** | 4300 km (2671 miles) |

**Juno** is a NASA New Frontiers mission to the planet Jupiter. It was originally proposed at a cost of approximately US$700 million (FY03) for a June 2009 launch. NASA budgetary restrictions resulted in Juno being re-scheduled to an August 2011 launch. The Atlas V rocket has been chosen to launch Juno in the Atlas V-551 configuration.

The spacecraft will be placed in a polar orbit to study the planet's composition, gravity field, magnetic field, and polar magnetosphere. Juno will also search for clues about how Jupiter formed, including whether the planet has a rocky core, the amount of water present within the deep atmosphere, and how the mass is distributed within the planet. Juno will also study Jupiter's deep winds, which can reach speeds of 600 km/h.

## Mission summary



Juno during construction phase, mounted on a rotating fixture

Juno's trajectory will use a gravity assist speed boost from Earth, accomplished through an Earth flyby two years after its 2011 launch, scheduled for 5 August. In 2016, the spacecraft will perform an orbit insertion burn to slow the spacecraft enough to allow capture into an 11-day polar orbit. Once Juno enters into its orbit, infrared and microwave instruments will begin to measure the thermal radiation emanating from deep within Jupiter's atmosphere. These observations will complement previous studies of the planet's composition by assessing the abundance and distribution of water, and therefore oxygen. While filling missing pieces of the puzzle of Jupiter's composition, this data also provides insight into the planet's origins. Juno will also investigate the convection that drives general circulation patterns in Jupiter's atmosphere. Meanwhile, other instruments aboard Juno will gather data about the planet's gravitational field and polar magnetosphere.

The Juno mission will conclude in 2018, after 32 orbits around Jupiter. Data analysis may continue beyond 2018.

## Scientific objectives

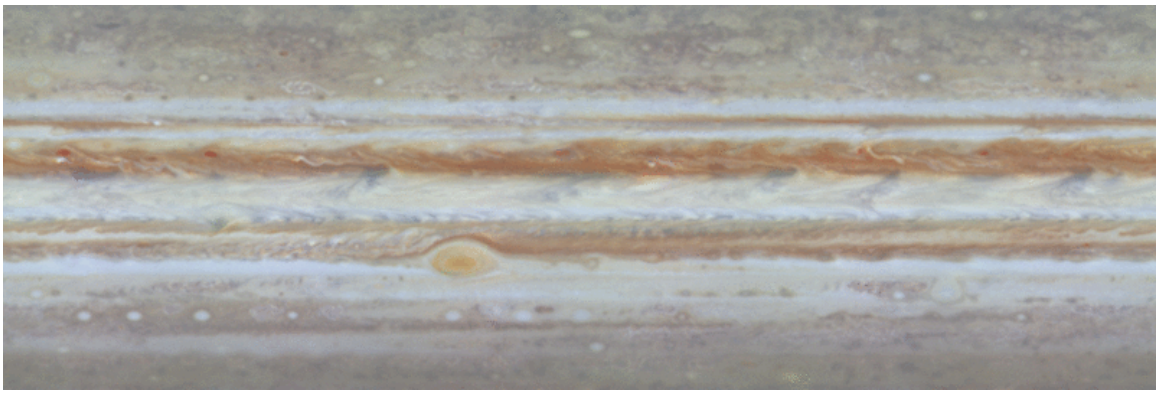
The Juno spacecraft's suite of seven science instruments will determine:

- The ratio of oxygen to hydrogen, effectively measuring the abundance of water in Jupiter, which will help distinguish among prevailing theories linking the gas giant's formation to the solar system.
- Obtain a better estimate of Jupiter's core mass, which will also help distinguish among prevailing theories linking the gas giant's formation to the solar system.
- Precisely map Jupiter's gravity to assess the distribution of mass in Jupiter's interior, including properties of the planet's structure and dynamics.
- Precisely map Jupiter's magnetic field to assess the origin and structure of the field and how deep in Jupiter the magnetic field is created. This experiment also will help scientists understand the fundamental physics of dynamo theory.
- Map the variation in atmospheric composition, temperature, structure, cloud opacity and dynamics to depths far greater than 100 bars at all latitudes.
- Characterize and explore the three dimensional structure of Jupiter's polar magnetosphere and its auroras.

## The team

Scott Bolton of the Southwest Research Institute in San Antonio, Texas is the Principal Investigator and is responsible for all aspects of the mission. The Jet Propulsion Laboratory in California manages the mission and Lockheed Martin Corporation is responsible for the spacecraft development. The mission is being carried out with the participation of several institutional partners.

## Scientific instruments



Zones, belts and vortices on Jupiter

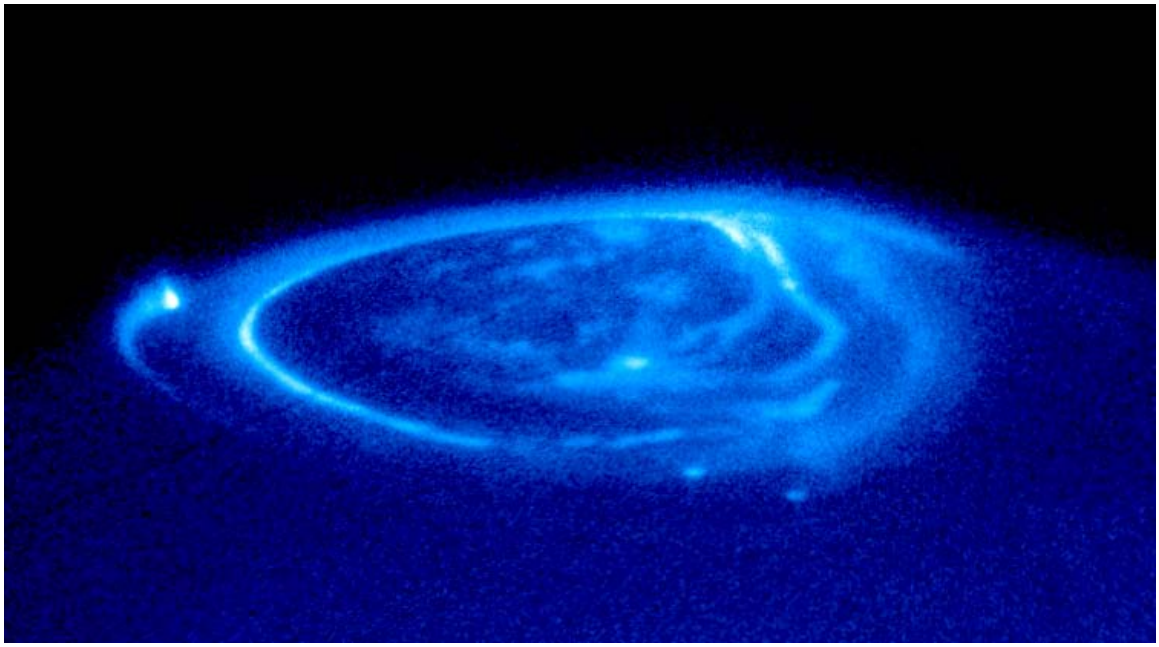


Image of Jupiter aurora in UV by the Hubble Space Telescope. Bright streaks and dots are caused by magnetic flux tubes connecting Jupiter to its largest moons: Io: bright streak on the far left . Ganymede: bright dot below center, Europa: dot on the right.

The Juno mission's science objectives will be achieved with a payload of eight instruments onboard the spacecraft:,

- Microwave radiometer (MWR)

  Jet Propulsion Laboratory, PI: Mike Janssen

- Jovian Infrared Auroral Mapper (JIRAM)

  Italian National Institute for Astrophysics

- Fluxgate Magnetometer (FGM) and Advanced Stellar Compass (ASC)

  NASA's Goddard Space Flight Center

- Jovian Auroral Distribution Experiment (JADE)

  Southwest Research Institute, PI: David McComas

- Jovian Energetic Particle Detector Instrument (JEDI)

  Applied Physics Laboratory

- Radio and Plasma Wave Sensor (WAVES)

University of Iowa

- Ultraviolet Imaging Spectrograph (UVS)

  Southwest Research Institute, PI: G. Randall Gladstone

- JunoCam (JCM)

  Malin Space Science Systems

## Solar panels

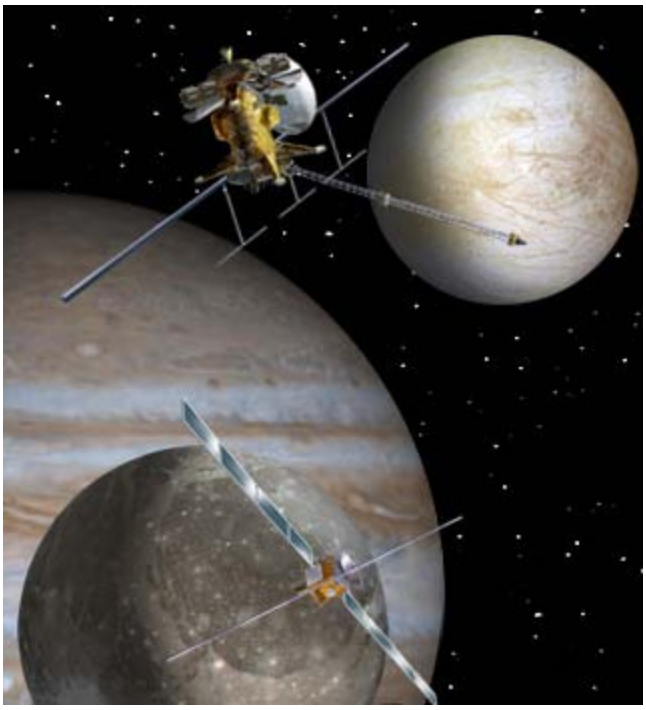
Juno will be the first mission to Jupiter using solar panels instead of the radioisotope thermoelectric generators (RTGs) used by Pioneer 10, Pioneer 11, the Voyager program, Cassini–Huygens, and the Galileo orbiter. Advances made in both solar cell technology and efficiency over the past several decades makes it economically feasible to use solar panels of practical size to provide power 5 Astronomical units from the Sun. In addition, RTGs are in short supply, limiting their availability for space missions. NASA plans several more projects involving RTGs, and the decision to use alternate technology on this mission is more practical and economical than political.

The Juno spacecraft uses three solar arrays symmetrically arranged around the spacecraft, which are stowed against the sides of the spacecraft for launch. Immediately after launch the arrays deploy. Two of the arrays have 4 panels each, and the third array has 3 panels with a magnetometer experiment in place of the fourth panel. The total area of the arrays is over 60 square metres (650 sq ft). This is enough to produce about 15 kilowatts (20 hp) while in Earth orbit, but only 486 watts (0.652 hp) when Juno arrives at Jupiter, declining to 420 watts (0.56 hp) as the radiation degrades the cells. The solar panels will remain in sunlight continuously from launch through to the end of the mission, except for short periods during the operation of the main engine.

## Chapter 2

# Europa Jupiter System Mission

**Europa Jupiter System Mission**



Artist concept of the Europa Jupiter System Mission: Jupiter Europa Orbiter (top) and Jupiter Ganymede Orbiter (bottom)

| | |
|---|---|
| **Operator** | Proposed joint ESA/NASA |
| **Mission type** | Multiple orbiters and lander |
| **Launch date** | 2020 (if funded) |
| **Mission duration** | Undefined |

The **Europa Jupiter System Mission** (**EJSM**, ESA-working title: **Laplace**) is a proposed joint NASA/ESA unmanned space mission slated to launch around 2020 for the

in-depth exploration of Jupiter's moons with a focus on Europa, Ganymede and Jupiter's magnetosphere. In February 2009 it was announced that NASA/ESA had given this mission priority ahead of the Titan Saturn System Mission (TSSM). The ESA contribution still faces funding competition from two other missions, the Laser Interferometer Space Antenna (LISA) and the International X-ray Observatory (IXO). In 2013 ESA will choose only one of these three missions for further funding, which is why NASA keeps a contingency plan of sending its part of the mission as a stand-alone project.

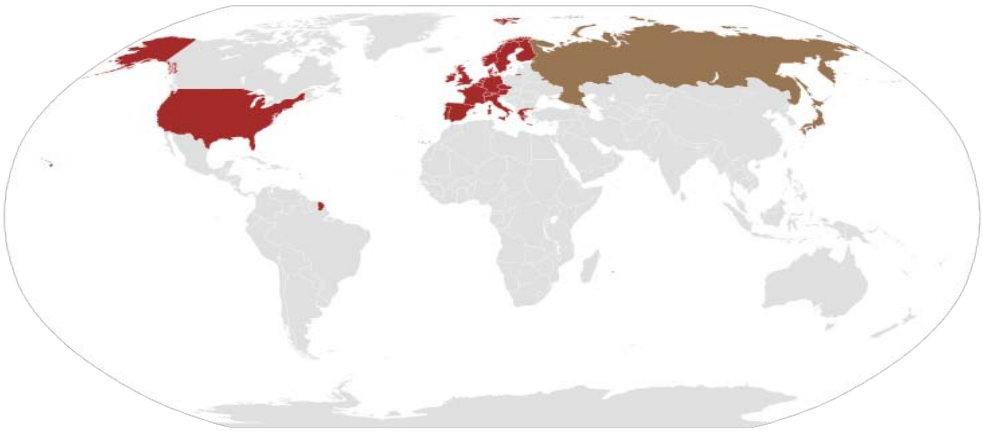
The Japan Aerospace Exploration Agency (JAXA) and the Russian Federal Space Agency (Roscosmos) have expressed their interest in contributing, although no deals have been finalized. Like the TSSM, the EJSM (considering an orbiter-only scenario and without a participation by Japan or Russia) is estimated to cost $4.45 billion, of which NASA contributes $3.8 billion (85%) and ESA $650 million (15%).

# Origins

In February 2008, NASA and ESA began joint investigations into sending a probe to study the icy satellites of the outer solar system under the title Outer Planet Flagship Mission. Two primary candidate missions were considered under the study: EJSM and TSSM, also known under the ESA designation TandEM.

On February 18, 2009 NASA and ESA jointly announced that both missions can proceed forward, but the EJSM is to be the first, departing Earth in 2020 and arriving at the Jupiter in 2026. The Titan mission is to be launched at later date.

# Mission architecture



A map showing all the nations which are either currently part of (red) or interested in becoming a part of (brown) the EJSM.

The most distinctive feature of the EJSM/Laplace-study, are its proposed two, possibly three, or even four separate orbiters/landers.

- **NASA**: Jupiter Europa Orbiter (JEO), planned to study Europa and Io.
- **ESA**: Jupiter Ganymede Orbiter (JGO), planned to study Ganymede and Callisto
- **JAXA**: Jupiter Magnetospheric Orbiter (JMO), planned to study Jupiter's magnetosphere.
- **Roscosmos**: Europa Lander, planned to land on Europa's surface for *in situ* studies.

The baseline EJSM architecture consists of JEO and JGO, which are proposed to be launched in 2020 and will execute an intricately choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. The JEO and JGO are separate and independent spacecraft developed, launched and operated by their respective organizations to work together. Their launch dates and interplanetary trajectories are not dependent on each other. While each flight system will focus on two of the four Galilean satellites, by operating together they allow full system coverage including Jupiter, its magnetosphere, and its rings.

Both satellites are to monitor dynamic phenomena such as Io's volcanoes and Jupiter's atmosphere, map the Jovian magnetosphere and its interactions with the Galilean satellites, and confirm the hypothesized water oceans beneath the ice shells of Europa and Ganymede. Should Japan (JAXA) join the project, JMO will explore the Jovian magnetosphere *in situ* as a template for an astrophysical magnetised disk and affording the opportunity for "3-point" investigations of the Jupiter system via synergistic observations with JGO and JEO.

## Objective

The objective is to determine whether the Jupiter system harbors habitable environments. The fundamental theme for EJSM can be further focused into science objectives relating to habitability (focusing on Europa and Ganymede). The main science objectives supporting this goal are:

- Characterize sub-surface oceans
- Characterize the ice shells and any subsurface water
- Characterize the deep internal structure for Ganymede and the intrinsic magnetic field
- Compare the exospheres, plasma environments, and magnetospheric interactions.
- Determine global surface compositions and chemistry
- Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.

## Possible addition of a Russian Europa lander

The Russian Federal Space Agency (Roscosmos) and the Russian Academy of Sciences are considering an independent Russian segment of the mission with the objective of delivering a lander to Europa, called Europa Lander. It would be separately launched by a Soyuz-class launcher relying on the ESA and/or NASA-orbiters to relay its data to Earth. A broad international involvement in the science payload and exploration tools of the descent module is envisaged. Depending on the available resources, a combination of a grinder on a robotic arm, or even a drill/thermal penetration system is envisaged in order to determine the characteristics of Europa's surface ice. Other landing scenarios suggest the use of high-velocity impactors which penetrate through the irradiated surface material to reach pristine ice. Once impacted, the probe can release a melting system to explore the shallow subsurface of Europa.

# Chapter 3

# Galileo (Spacecraft)

### *Galileo* Orbiter

*Galileo* is prepared for mating with the IUS booster

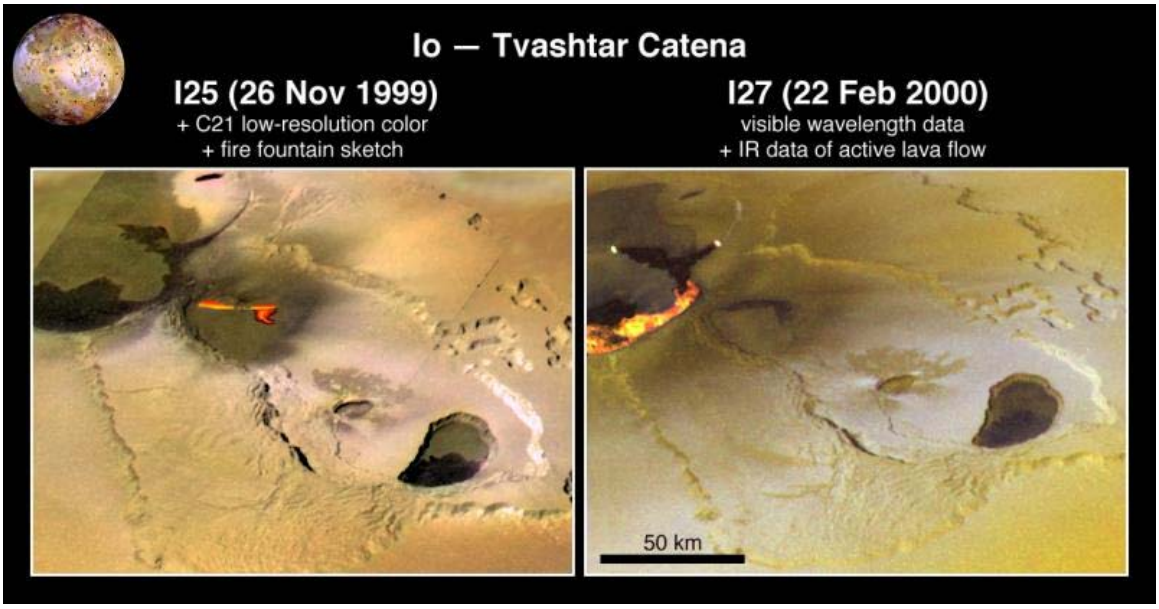
| | |
|---|---|
| **Operator** | NASA |
| **Mission type** | Orbiter, Fly-by |
| **Flyby of** | Venus, Earth, 951 Gaspra, 243 Ida |
| **Satellite of** | **Jupiter** |
| **Orbital insertion date** | 1995-12-08 01:20:00 UTC |
| **Launch date** | 1989-10-18 16:53:00 UTC |
| **Launch vehicle** | Space Shuttle Atlantis<br>Inertial Upper Stage |
| **Launch site** | KSC Launch Complex 39B<br>Kennedy Space Center |
| **Mission duration** | December 8, 1995 -<br>September 21, 2003<br>(deorbited 2003-09-21 18:57:00 UTC) |

| | |
|---|---|
| **COSPAR ID** | 1989-084B |
| **Homepage** | *Galileo* Project Home Page |
| **Mass** | 2,380 kg (5,200 lb) |
| **Power** | 570 W (2 RTGs) |

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

*Galileo* and Inertial Upper Stage in space

The four largest moons of Jupiter photographed by Galileo




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

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

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

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

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

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

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

## Mission overview

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

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

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

## The *Galileo* spacecraft

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

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

## Command and data handling

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

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

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

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

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

## Propulsion

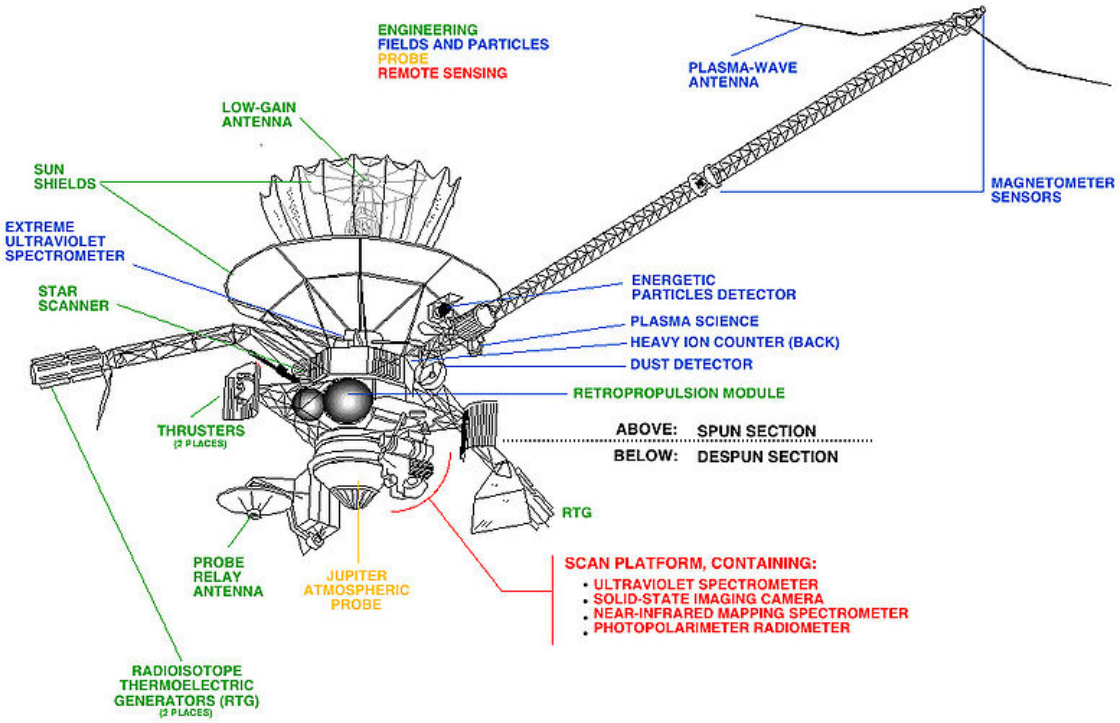
The Propulsion Subsystem consisted of a 400 N main engine and twelve 10 N thrusters together with propellant, storage and pressurizing tanks, and associated plumbing. The 10

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

## Electrical power

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

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




Overview of *Galileo*'s components

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

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

## Instrumentation overview

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

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

## Instrumentation details

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

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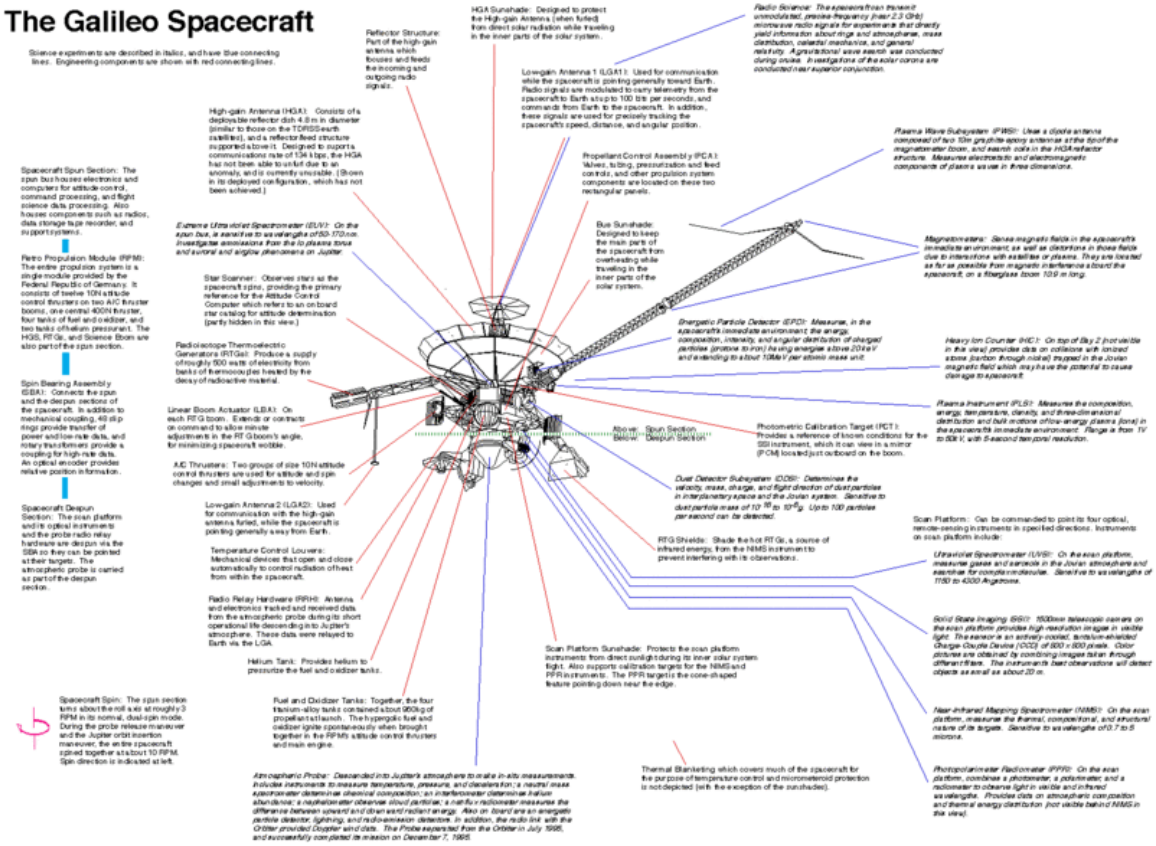



Highly detailed diagram of *Galileo* instruments and subsystems

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)**

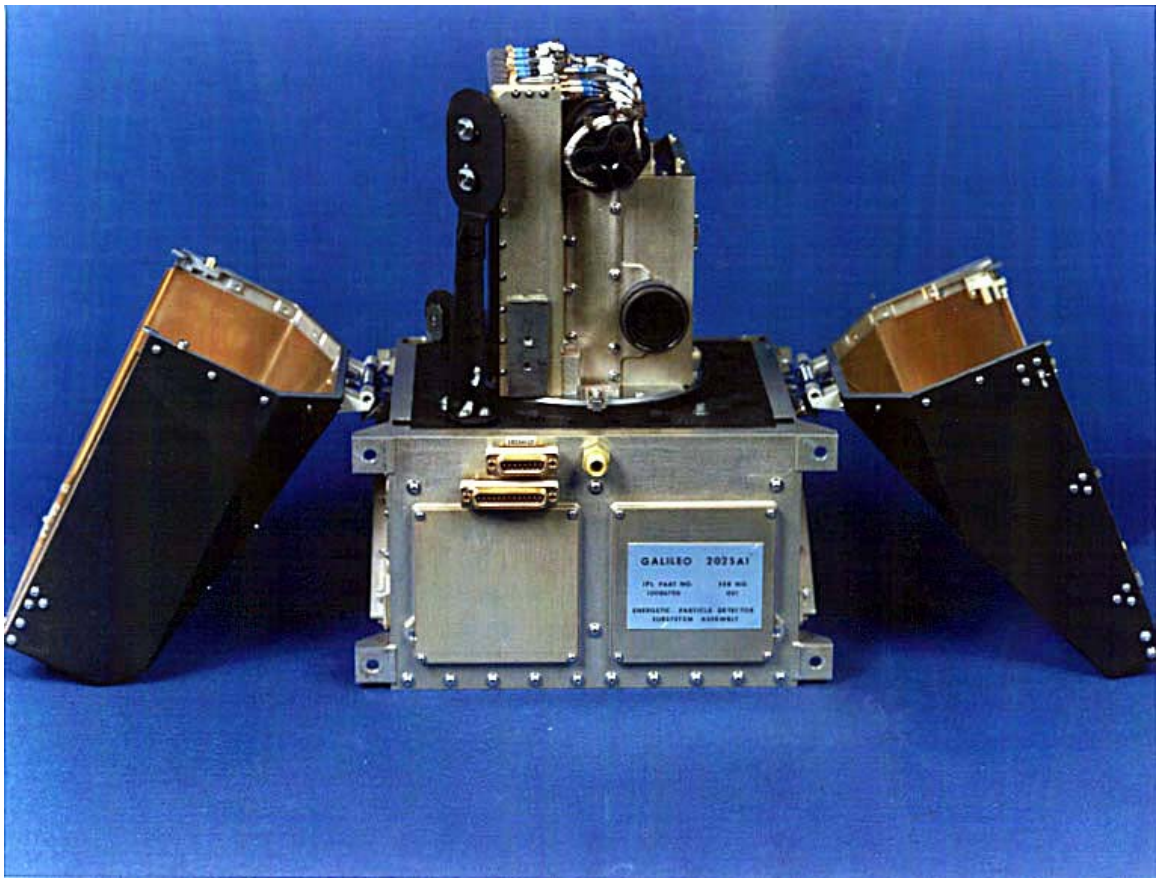
The Cassegrain telescope of the UVS has a 250 mm aperture and collects light from the observation target. Both the UVS and EUV instruments use a ruled grating to disperse this light for spectral analysis. This light then passes through an exit slit into photomultiplier tubes that produce pulses or "sprays" 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)**

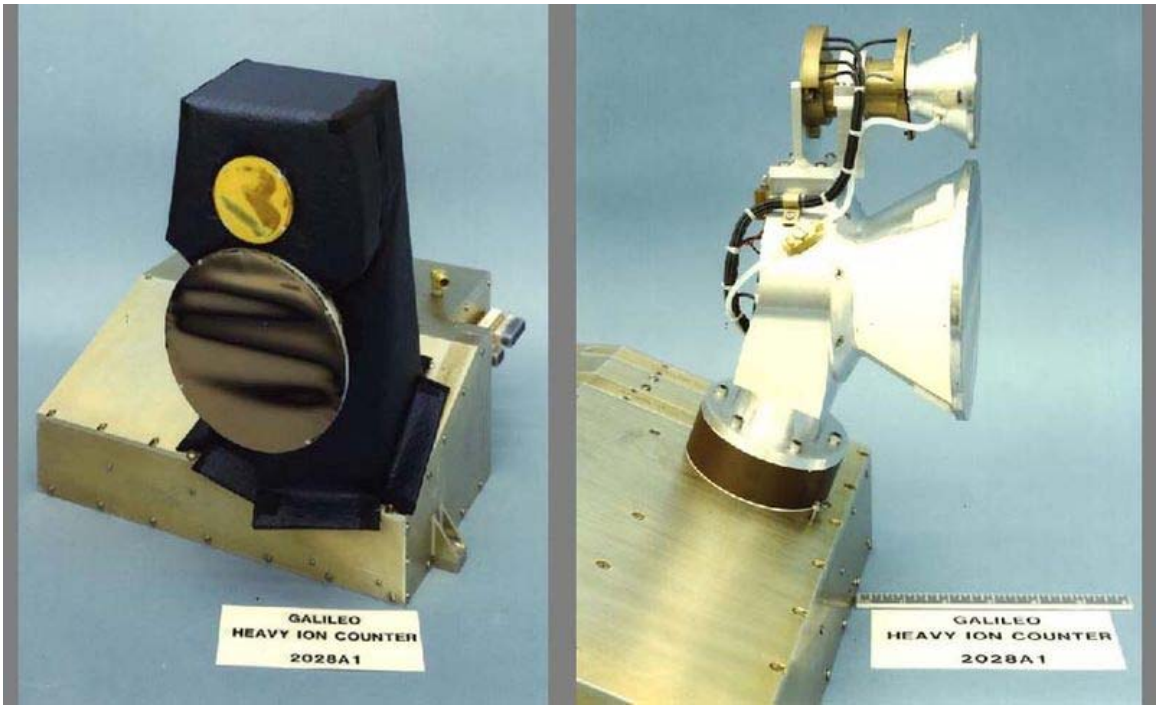
The PPR has seven radiometry bands. One of these uses no filters and observes all the radiation, both solar and thermal. Another band lets only solar radiation through. The difference between the solar- plus-thermal and the solar-only channels gives the total thermal radiation emitted. The PPR also measured 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)**

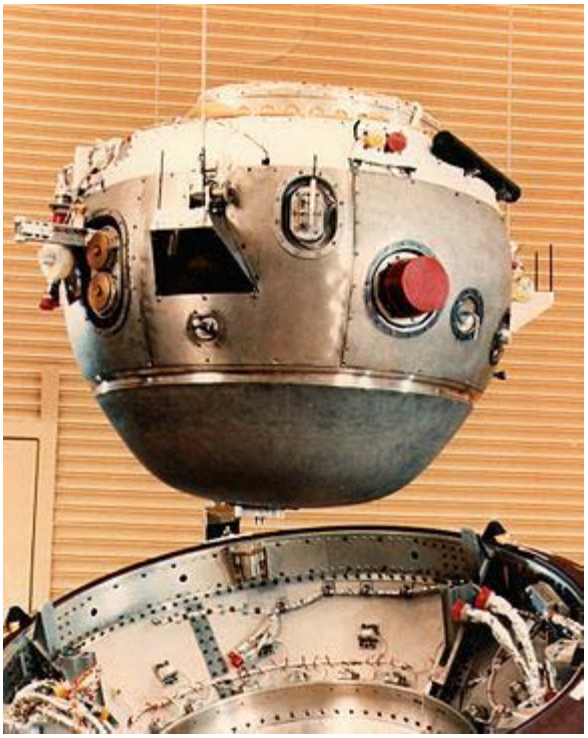
The PLS uses seven fields of view to collect charged particles for energy and mass analysis. These fields of view cover most angles from 0 to 180 degrees, fanning out from the spin axis. The rotation of the spacecraft carries each field of view through a full circle. The PLS will measure particles in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

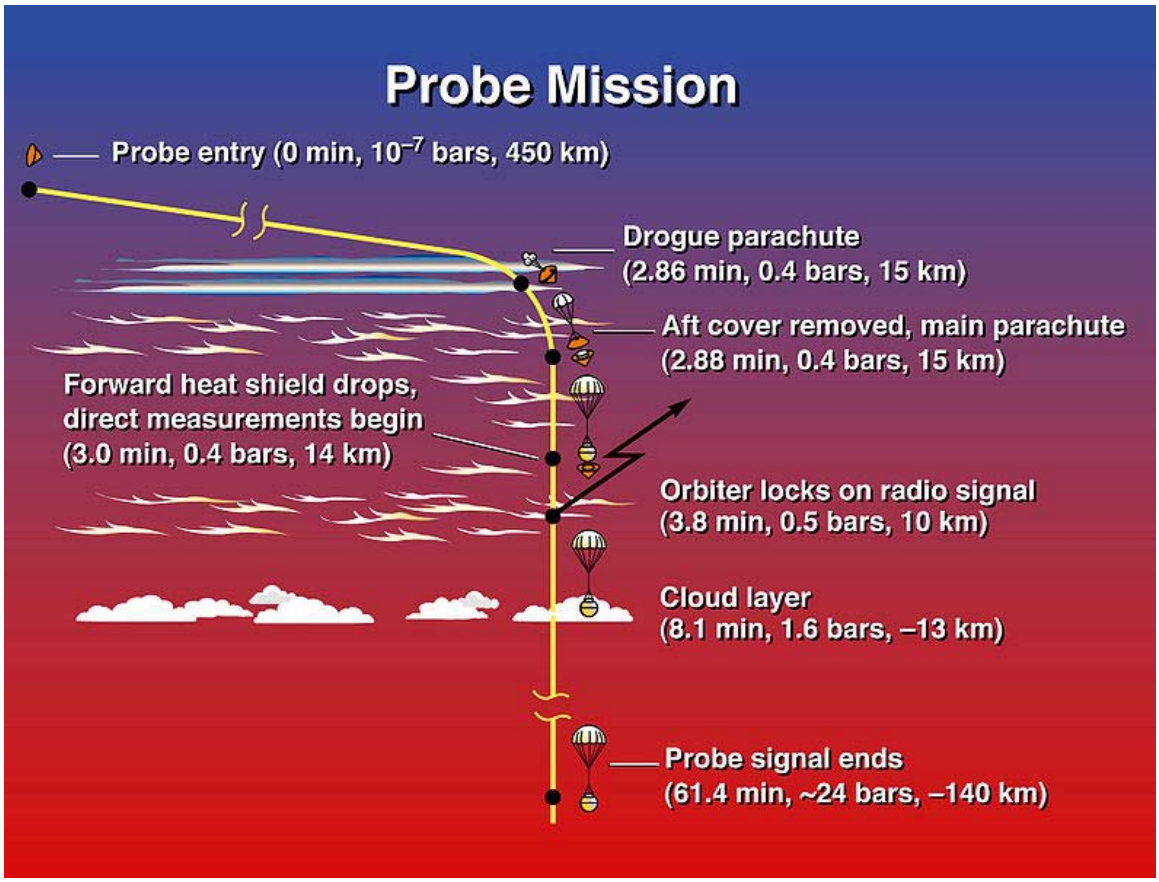
### *Galileo* Probe



The *Galileo* Probe Descent Module

| | |
|---|---|
| **Operator** | NASA |
| **Mission type** | Atmospheric probe |
| **Launch date** | July 13, 1995 |
| **Launch vehicle** | Space Shuttle Atlantis<br>Inertial Upper Stage<br>Galileo Orbiter |
| **Launch site** | KSC Launch Complex 39B<br>Kennedy Space Center |
| **Mission duration** | December 7, 1995<br>(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.

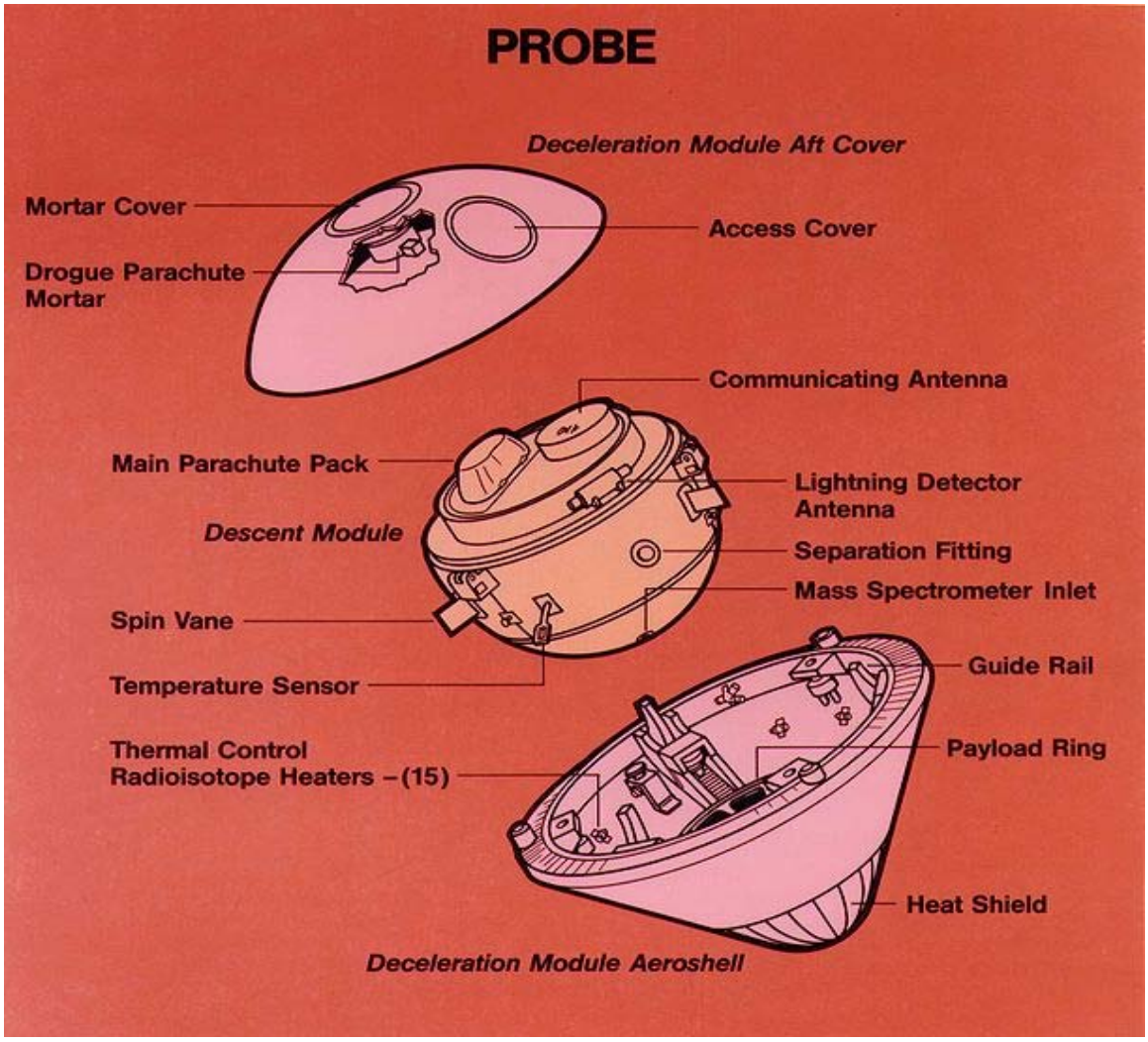



Diagram of *Galileo* atmospheric entry probe instruments and subsystems

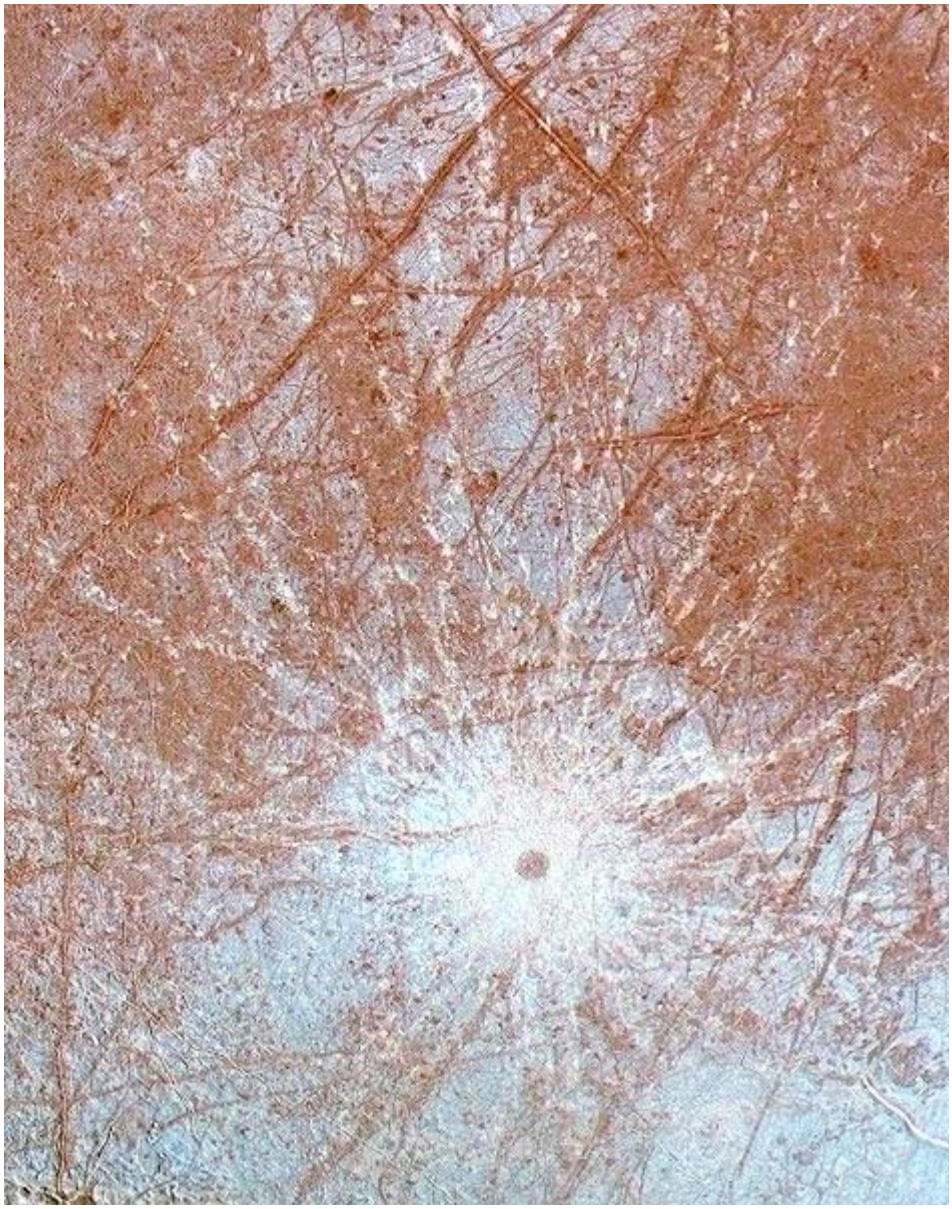
The probe included six instruments for taking data on its plunge into Jupiter:

- 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.

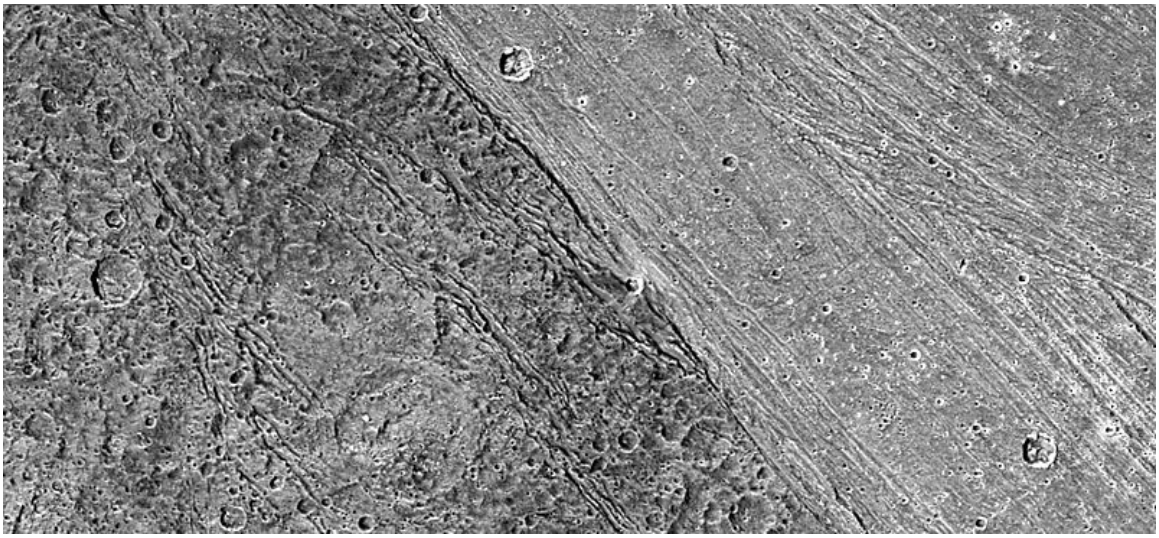
Total data returned from the probe was about 3.5 megabits (~458752 bytes). The probe stopped transmitting before the line of sight link with the orbiter was cut. The likely proximal cause of the final probe failure was overheating, which sensors indicated before signal loss.

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.

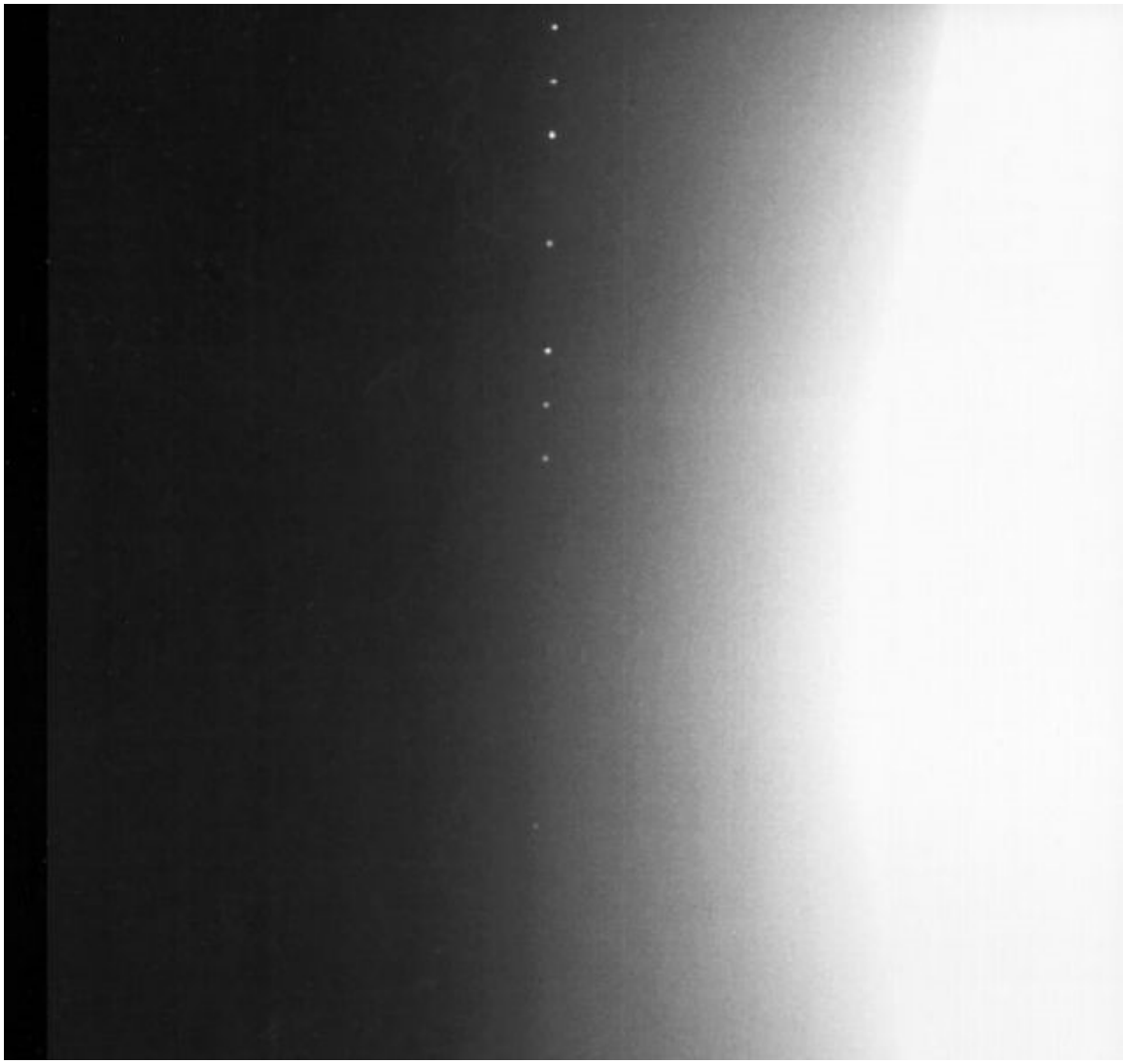


Image taken by *Galileo* of Earth during GOPEX test clearly showing bright laser pulses coming from a transmitting telescope on the night side. *Galileo'*s imager was panned downward during the exposure to separate the pulses, thus blurring earth's image on the right.

## 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.

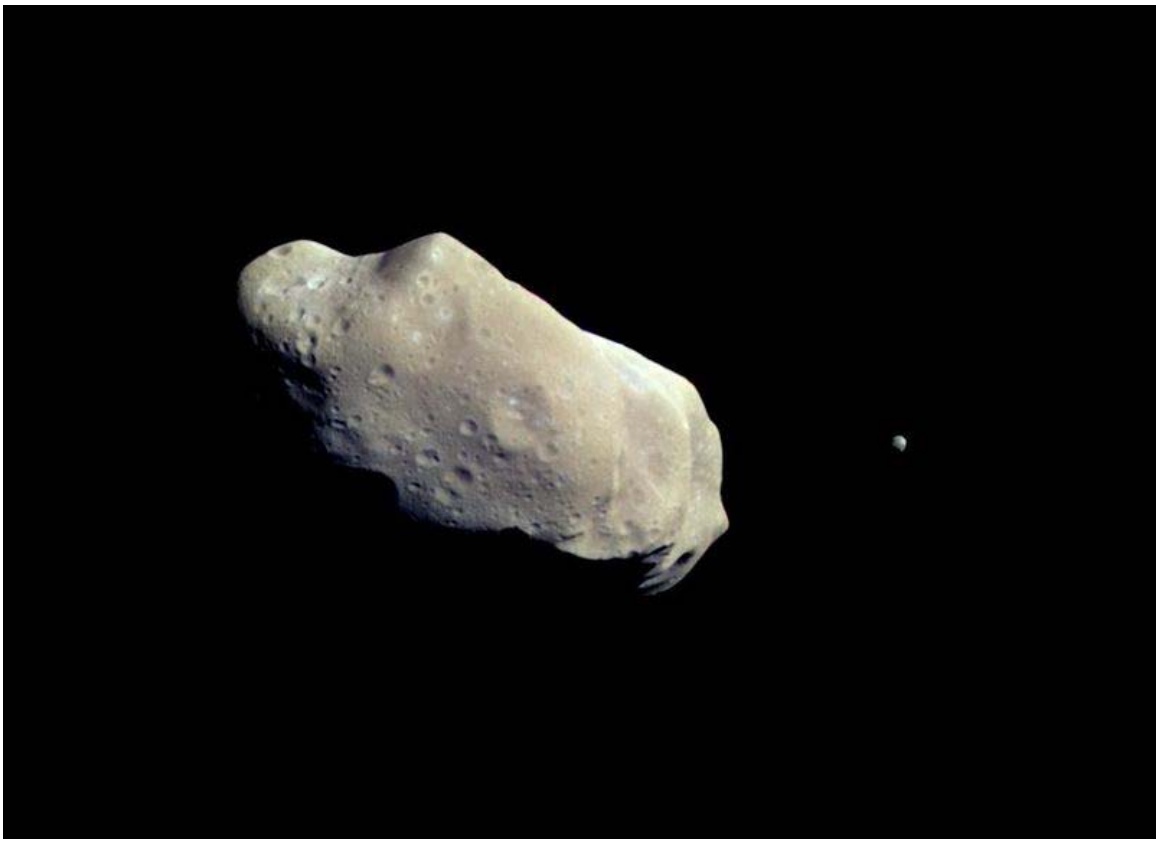
## Asteroid encounters

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**

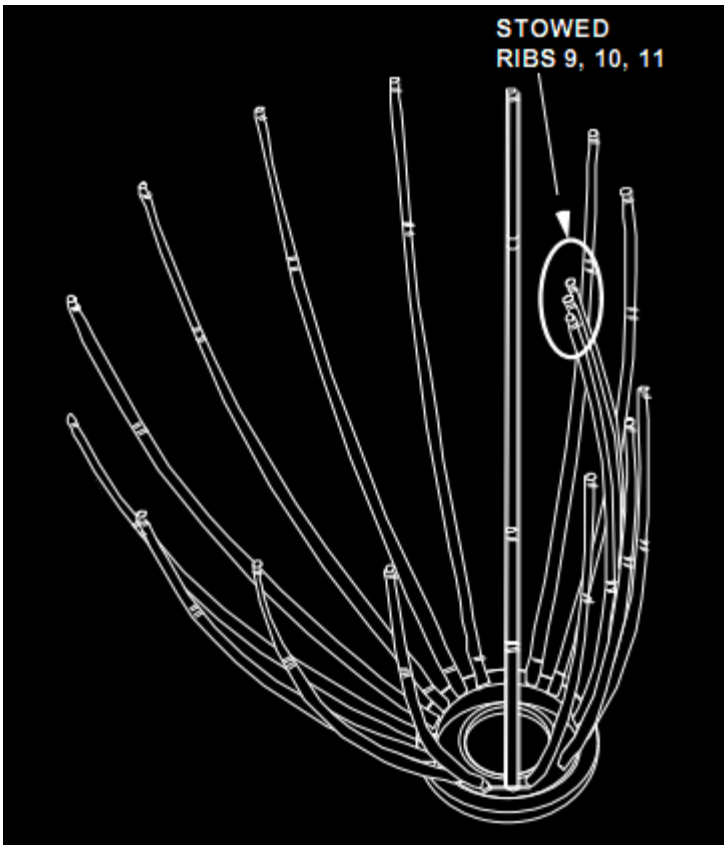


NASA image of 243 Ida. The tiny dot to the right is its moon, Dactyl.

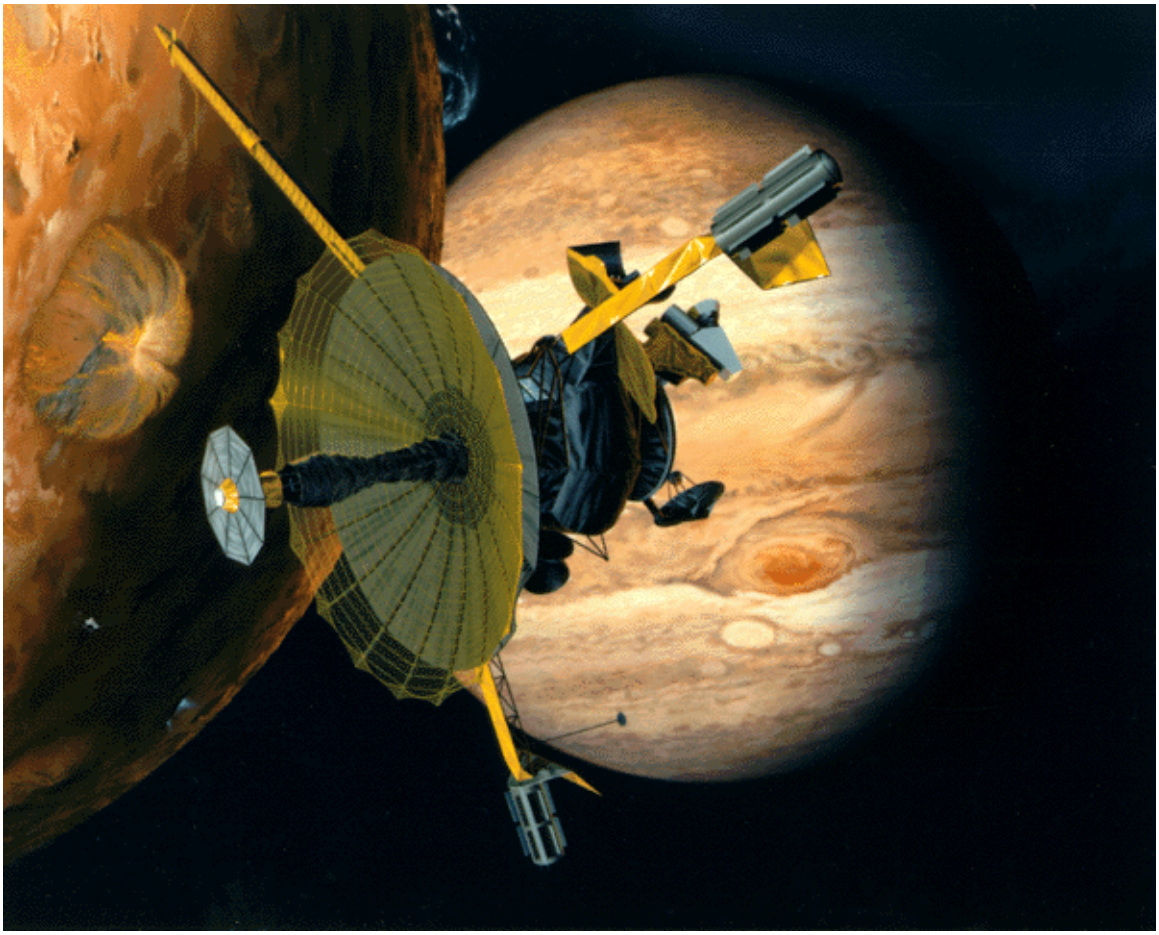
Twenty-two months after the Gaspra encounter, on August 28, 1993, *Galileo* flew within 2,400 kilometers (1,500 miles) of asteroid 243 Ida. The probe discovered that Ida had a small moon, dubbed Dactyl, only 1.4 km in diameter which was the first asteroid moon discovered. Measurements using *Galileo'*s 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

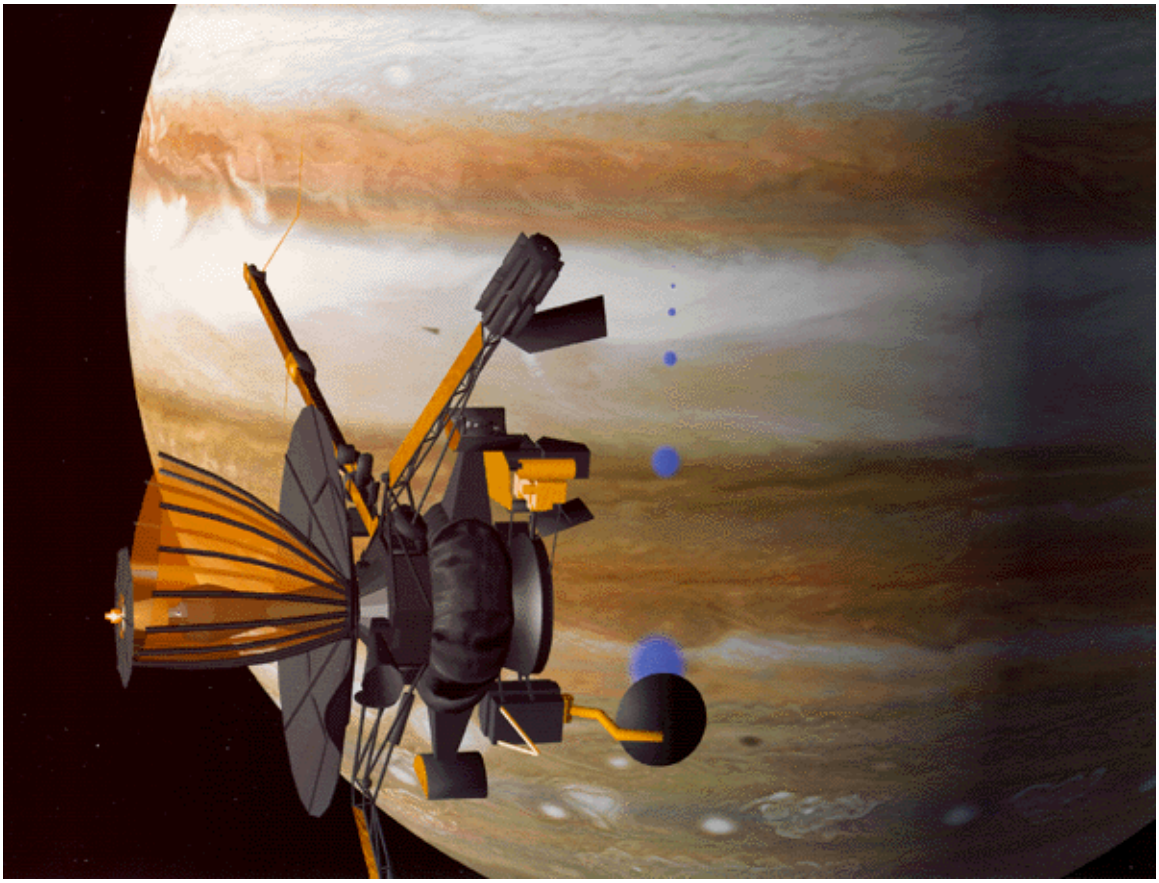
## Main antenna failure




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 ($10 \times 10^{-21}$ watts). Through implementation of sophisticated data compression techniques, arraying of several Deep Space Network antennas and sensitivity upgrades of receivers used to listen to *Galileo*'s signal, data throughput was increased to a maximum of 160 bits per second. The data collected on Jupiter and its moons was stored in the on board tape recorder, and transmitted back to Earth during the long apozene portion of the probe's orbit using the

low-gain antenna. At the same time, measurements were made of Jupiter's magnetosphere and transmitted back to Earth. The reduction in available bandwidth reduced the total amount of data transmitted throughout the mission to about 30 gigabytes and reduced the number of pictures that were transmitted significantly; in all, only around 14,000 images were returned.

## Tape recorder anomalies and remote repair

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

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

### Other radiation related anomalies

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

### Near failure of atmospheric probe parachute

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

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

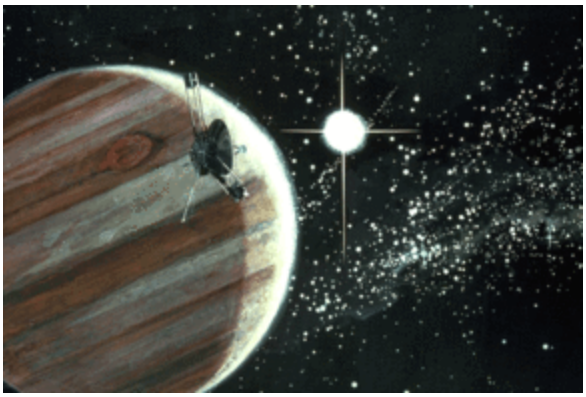
## *Galileo'*s end

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

# Chapter 4

# 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<br>(38 years, 11 months, and 21 days ago) |
| **Launch vehicle** | Atlas/Centaur/TE364-4 |
| **Launch site** | Space Launch Complex 36A<br>Cape Canaveral Air Force Station |
| **Mission duration** | Mar 2, 1972 - Jan 23, 2003<br>(30 years, 10 months, 22 days)<br>(lost communication)<br>Jupiter flyby<br>*(completed 1974-01-01)* |

| | |
|---|---|
| | Interstellar mission<br>*(completed 1997-03-31)* |
| **COSPAR ID** | 1972-012A |
| **Homepage** | Pioneer Project website(archived)<br>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

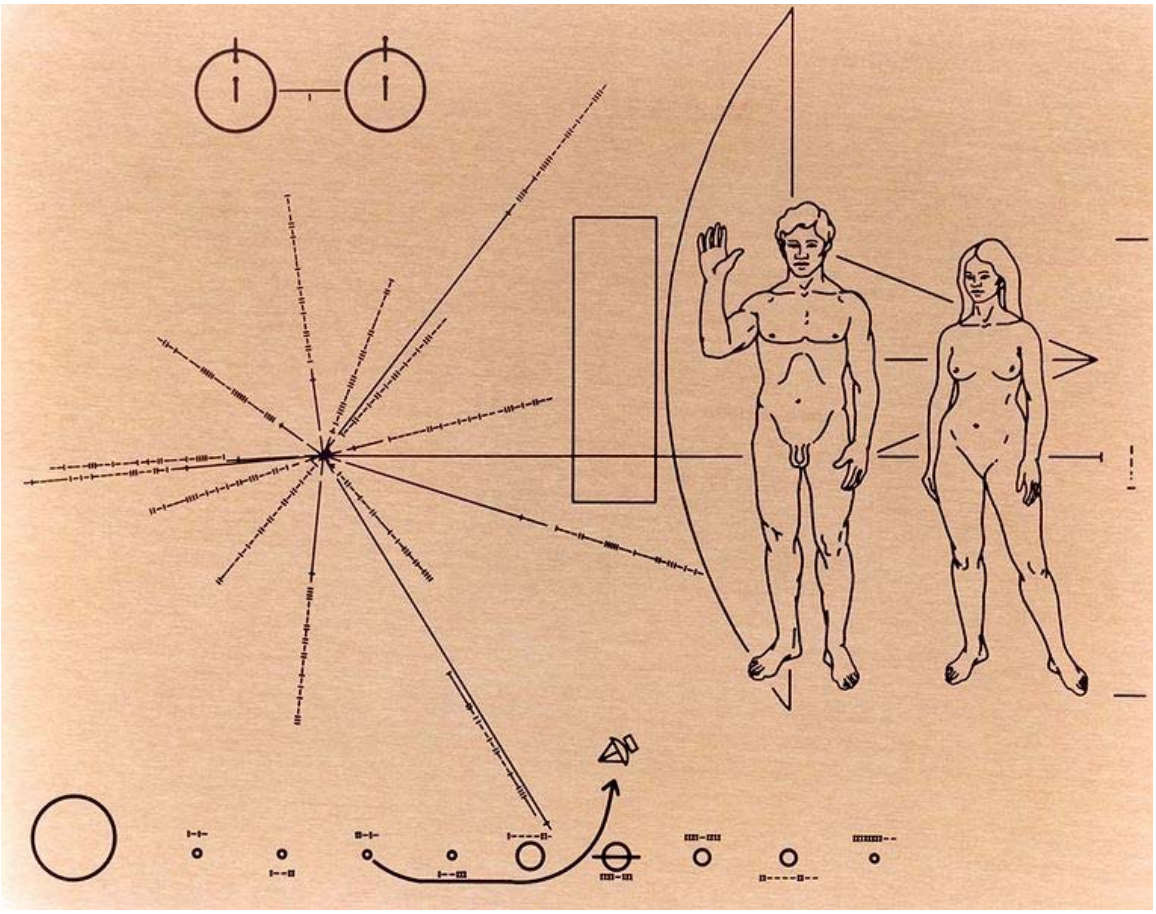
Approved in February 1969, *Pioneer 10* and twin probe *Pioneer 11*, were the first to be designed for exploring the outer solar system. Yielding to multiple proposals throughout the 1960s, early mission objectives were defined as:

- 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.

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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.

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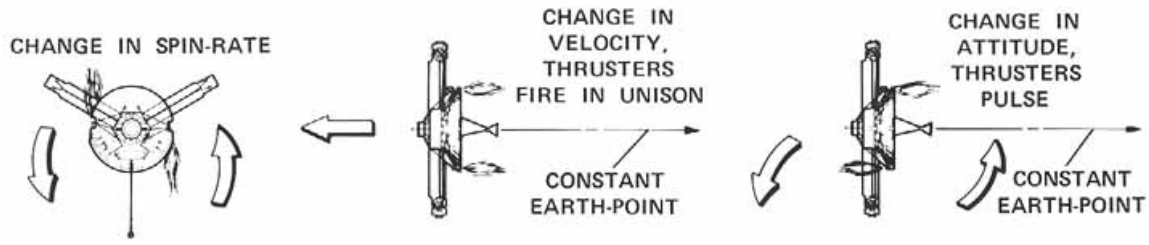



Orientation of the spacecraft was maintained with six 4.5 N, hydrazine monopropellant thrusters: pair one maintained a constant spin-rate of 4.8-rpm, pair two controlled the forward thrust, pair three controlled attitude. Information for the orientation was provided by a star sensor able to reference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

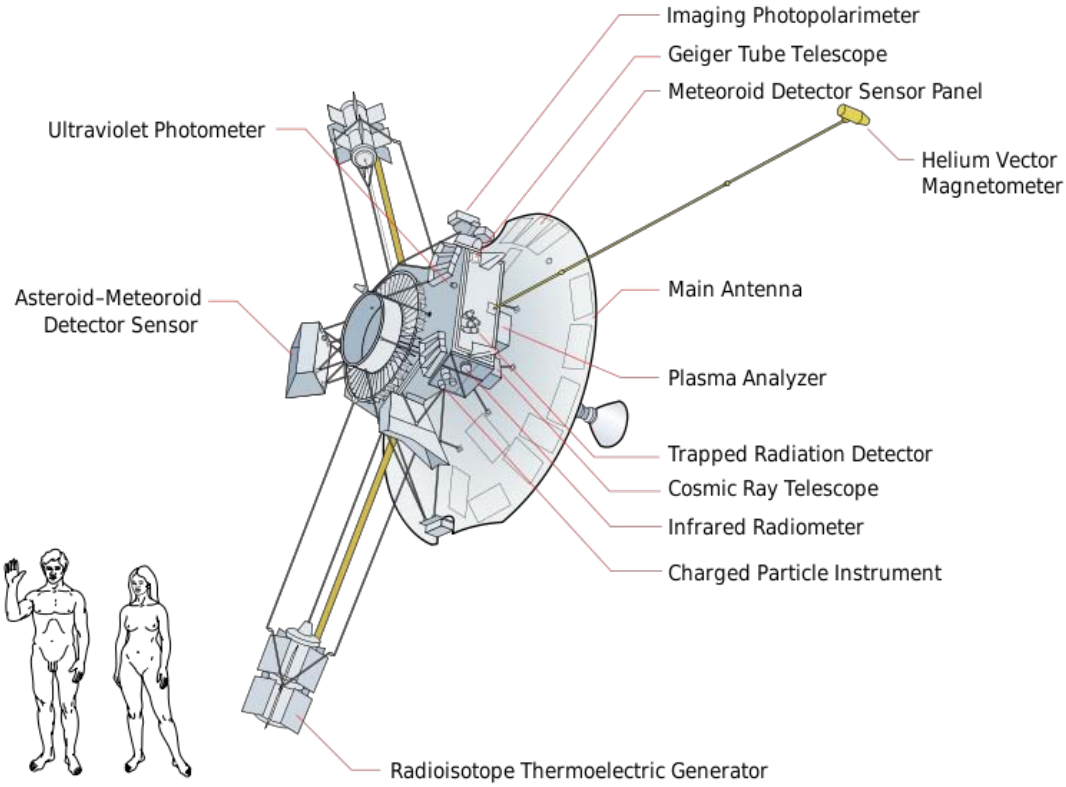
- **Principal investigator:** Tom Gehrels / University of Arizona
- **Data:** NSSDC data archive list

## Infrared Radiometer

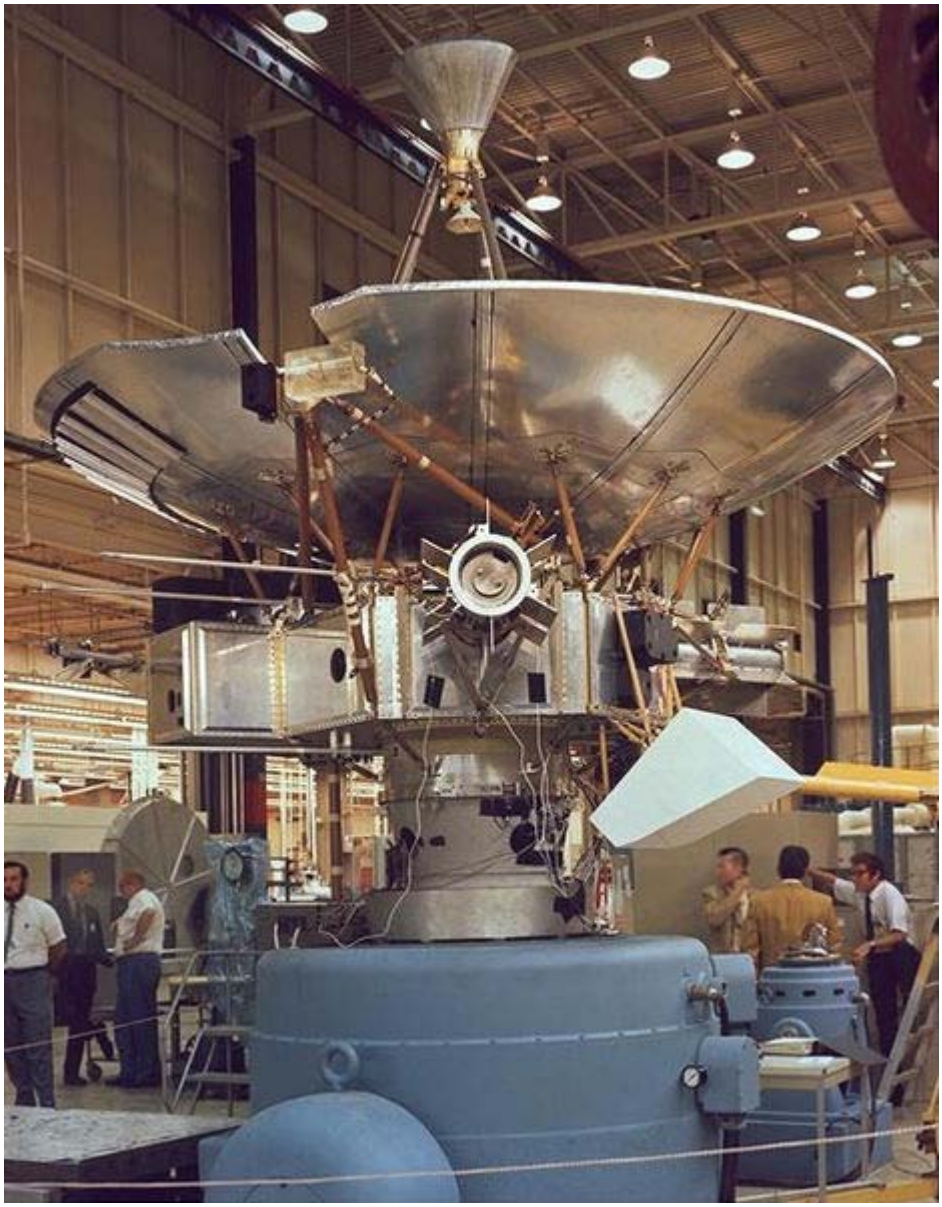
Provides information on cloud temperature and the output of heat from Jupiter.

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

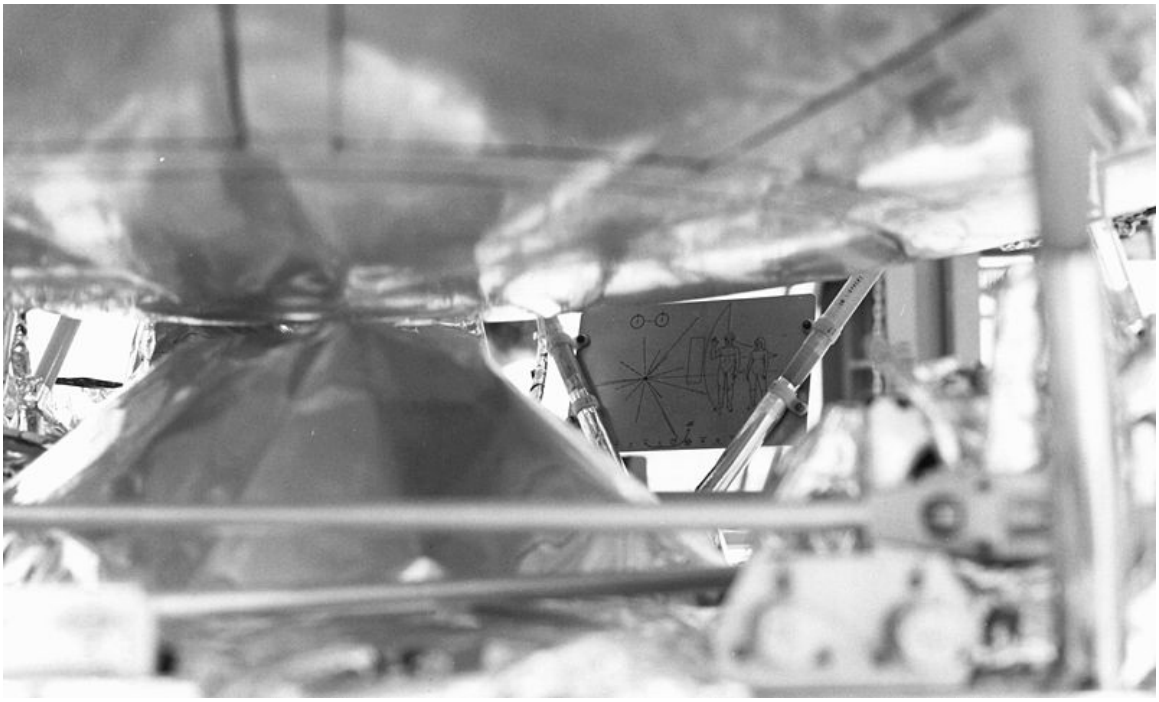
### Images of the spacecraft




*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

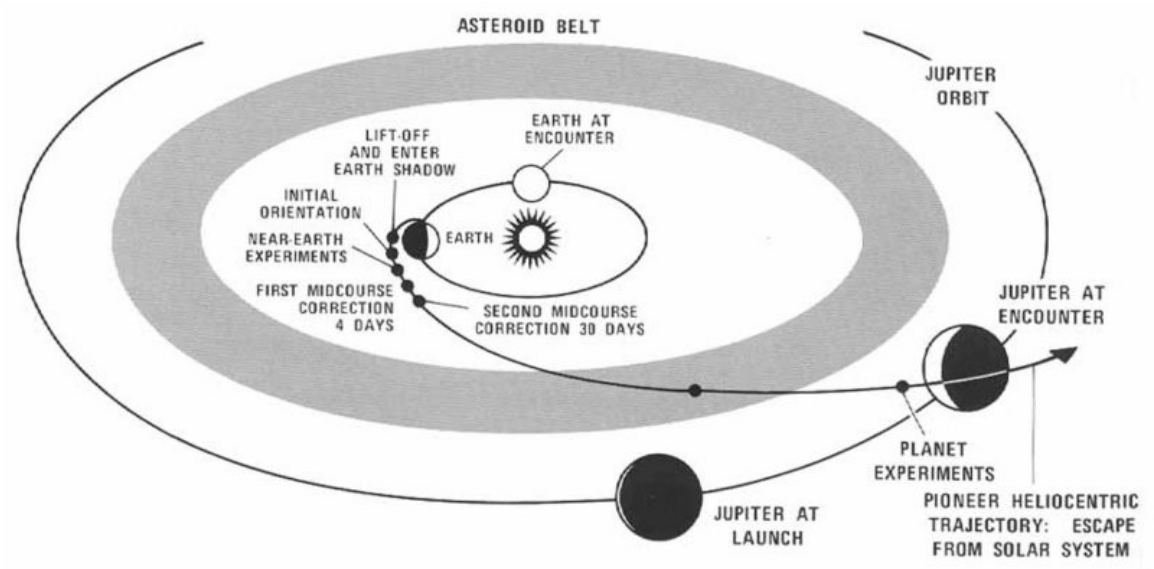
**Timeline of travel**

| 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. |

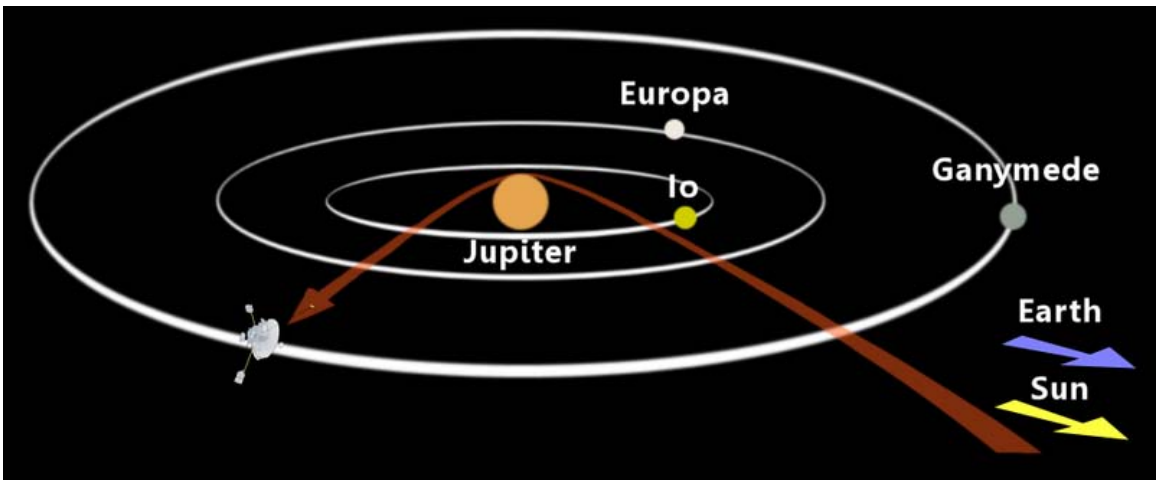
## Launch and trajectory

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



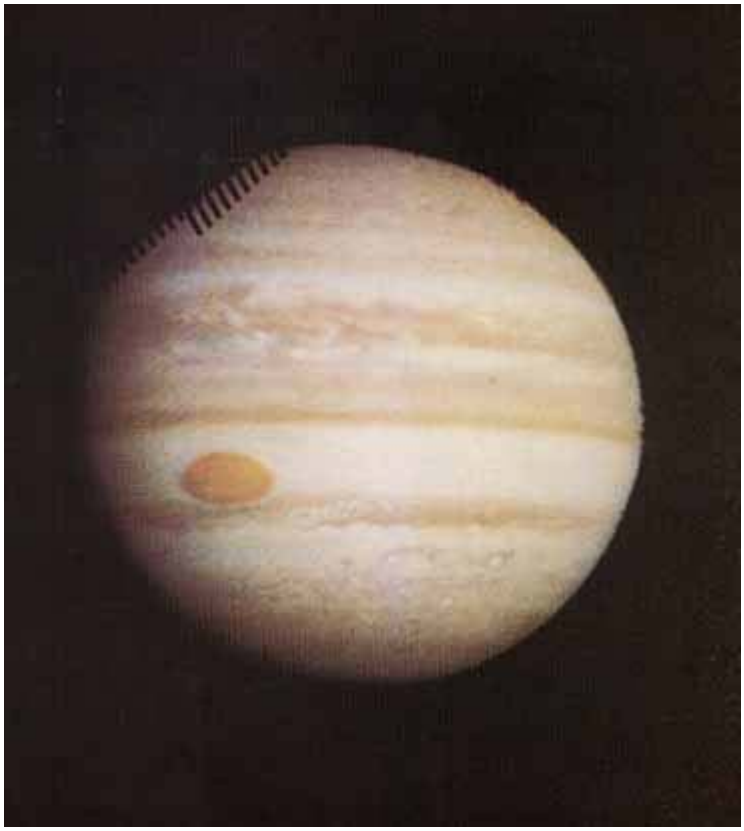

*Pioneer 10* trajectory through the Jovian system

## Encounter with Jupiter

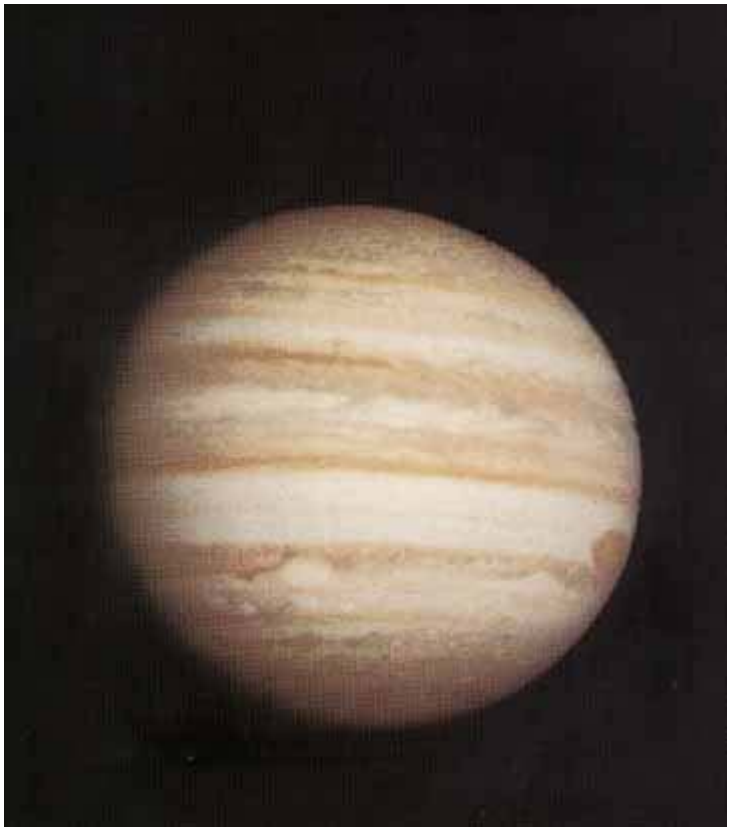
In November and December 1973, *Pioneer 10* began transmitting images of Jupiter back to Earth. 500 images of Jupiter had been received by December 2, 1973, revealing little detail. However, within the 48 hours prior to closest approach, the probe exceeded the resolution of Earth based observations,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



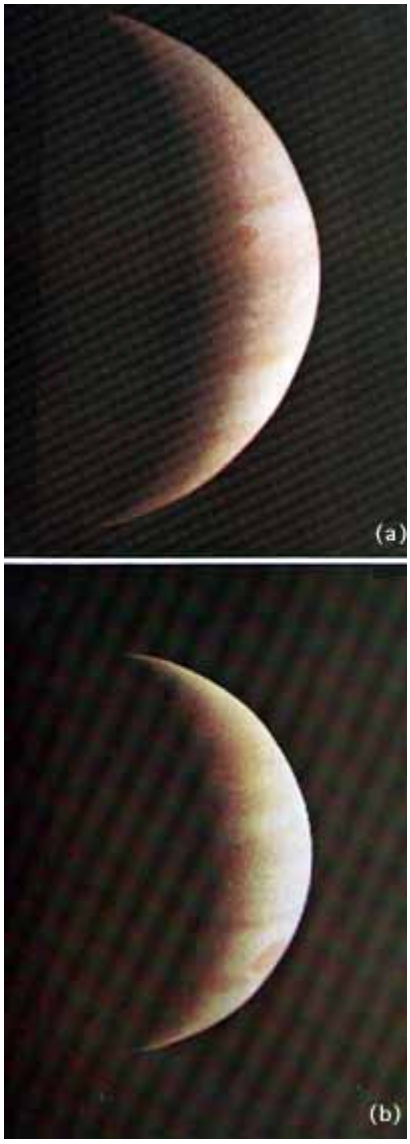
Jupiter encounter (frame 2)



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 5

# Pioneer 11

**Pioneer 11**

Pioneer 11 at Saturn (artist's impression)

| | |
|---|---|
| **Operator** | ARC / NASA |
| **Major contractors** | TRW |
| **Mission type** | Flyby |
| **Flyby of** | Jupiter, Saturn |
| **Launch date** | 1973-04-06 02:11:00 UTC<br>(37 years, 10 months, and 18 days ago) |
| **Launch vehicle** | Atlas/Centaur/TE364-4 |
| **Launch site** | Space Launch Complex 36A<br>Cape Canaveral Air Force Station |
| **Mission duration** | Apr 6, 1973 - Sep 30, 1995<br>(22 years, 5 months, 25 days)<br>(lost communication)<br>Jupiter flyby<br>*(completed 1975-01-01)*<br>Saturn flyby |

| | |
|---|---|
| | *(completed 1979-10-05)* |
| | Interstellar mission |
| | *(completed 1995-09-30)* |
| **COSPAR ID** | 1973-019A |
| **Homepage** | Pioneer Project website(archived)<br>NASA Archive |
| **Mass** | 259 kg (571 lb) |
| **Power** | 165.0 W (4 SNAP-19 RTGs) |

***Pioneer 11*** (also known as *Pioneer G*) was a 259-kilogram (569 lb) robotic space probe launched by NASA on April 6, 1973 to study the asteroid belt, the environment around Jupiter and Saturn, solar wind, cosmic rays, and eventually the far reaches of the solar system and heliosphere. It was the first probe to encounter Saturn and the second to fly through the asteroid belt and by Jupiter. Due to power constraints and the vast distance of the probe, communication has been lost since November 30, 1995.

# Mission background

## History

Approved in February 1969, *Pioneer 11* and twin probe *Pioneer 10*, 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.

Subsequent planning for an encounter with Saturn added many more goals:

- Map the magnetic field of Saturn and determine its intensity, direction, and structure.
- Determine how many electrons and protons of various energies are distributed along the trajectory of the spacecraft through the Saturn system.
- Map the interaction of the Saturn system with the solar wind.
- Measure the temperature of Saturn's atmosphere and that of Titan, the large satellite of Saturn.
- Determine the structure of the upper atmosphere of Saturn where molecules are expected to be electrically charged and form an ionosphere.

- Map the thermal structure of Saturn's atmosphere by infrared observations coupled with radio occultation data.
- Obtain spin-scan images of the Saturnian system in two colors during the encounter sequence and polarimetry measurements of the planet.
- Probe the ring system and the atmosphere of Saturn with S-band radio waves at occultation.
- Determine more precisely the masses of Saturn and its larger satellites by accurate observations of the effects of their gravitational fields on the motion of the spacecraft.
- As a precursor to the Mariner Jupiter/Saturn mission, verify the environment of the ring plane to find out where it may be safely crossed by the Mariner spacecraft without serious damage.

*Pioneer 11* 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.

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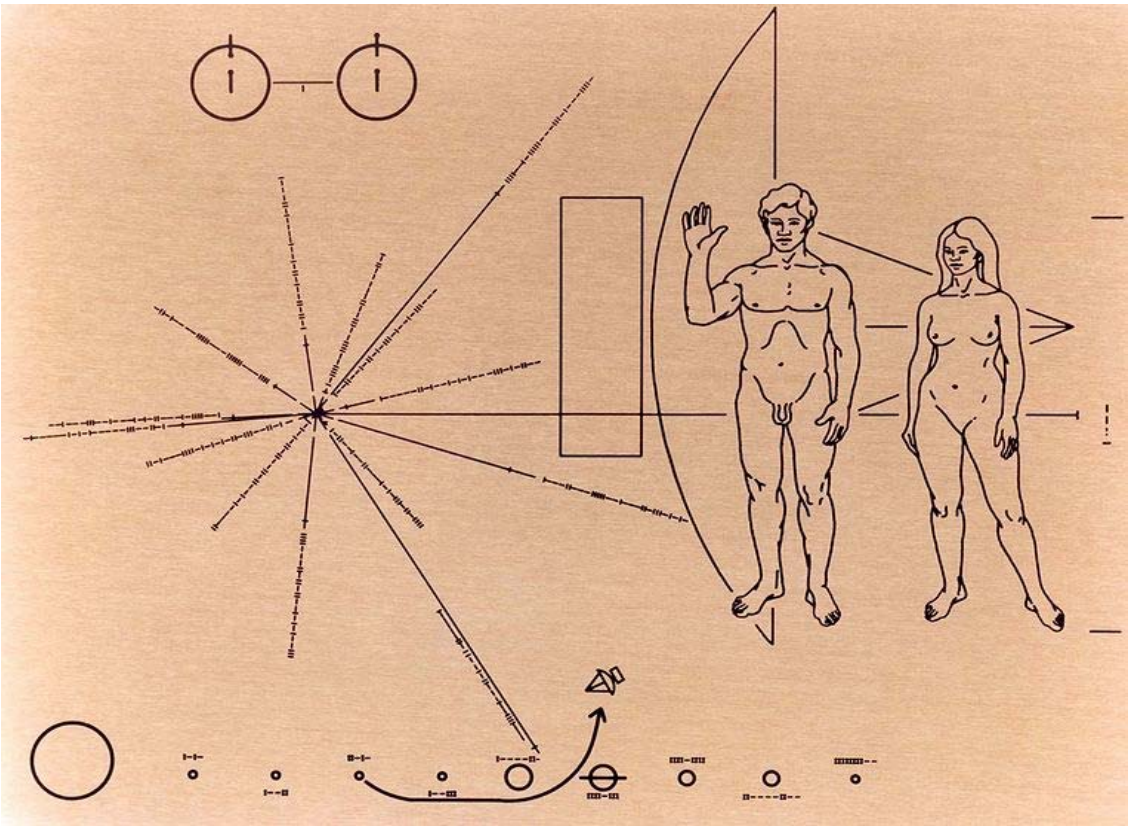

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plaques feature the nude figures of a human male and female along with several symbols that are designed to provide information about the origin of the spacecraft.

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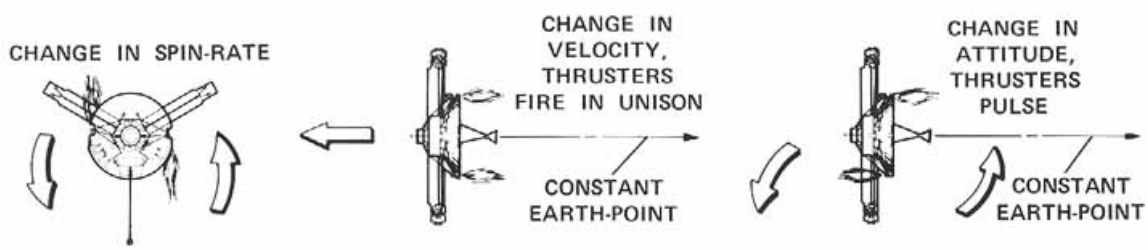


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**Scientific instruments**

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.

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

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- **Principal investigator:** James Van Allen / University of Iowa (website)
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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 hourly data archive, NSSDC Saturn 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.

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- **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
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## 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
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## 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.

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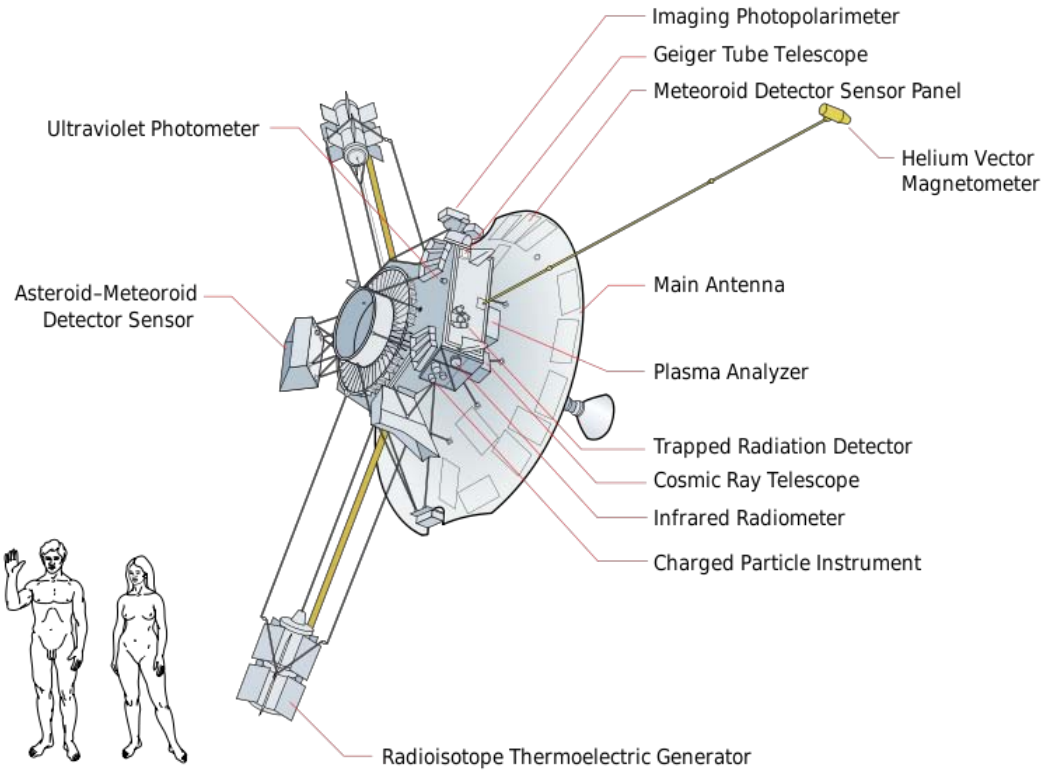
Provides information on cloud temperature and the output of heat from Jupiter.

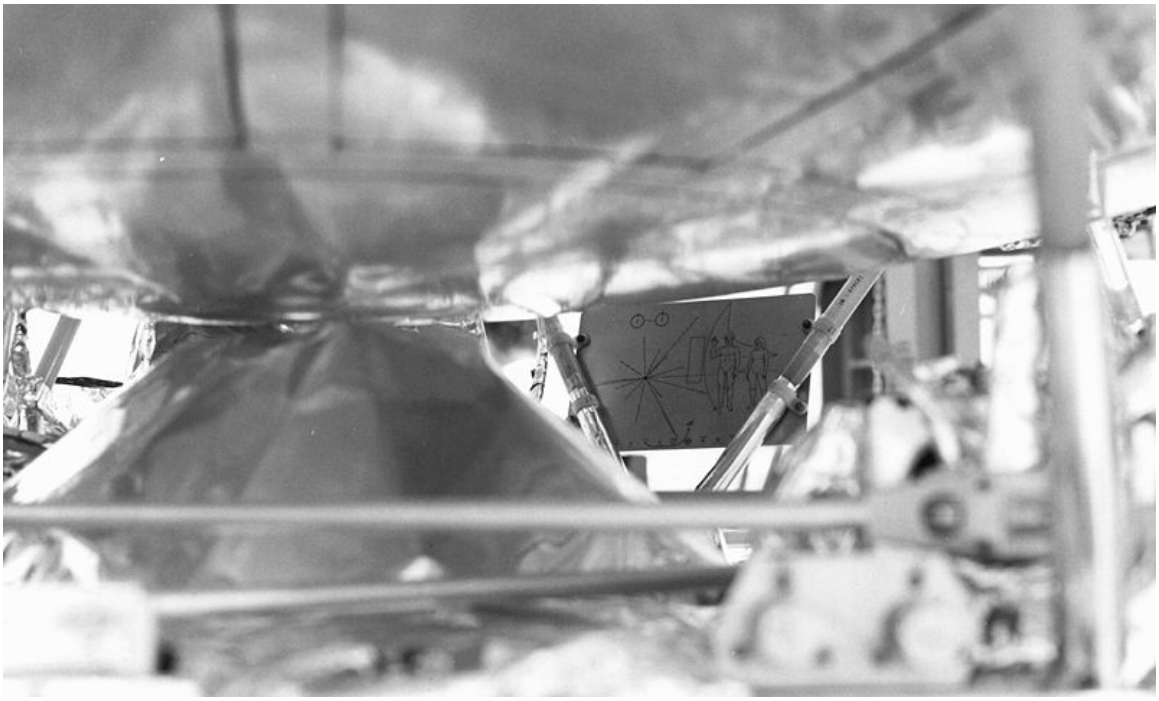
- **Principal investigator:** Andrew Ingersoll / California Institute of Technology

**Images of the spacecraft**




*Pioneer 11* spacecraft design

*Pioneer 11* spin stabilization testing



The Pioneer plaque fixed to the space probe

*Pioneer 11* being encapsulated for launch

# Mission profile

## Launch and trajectory

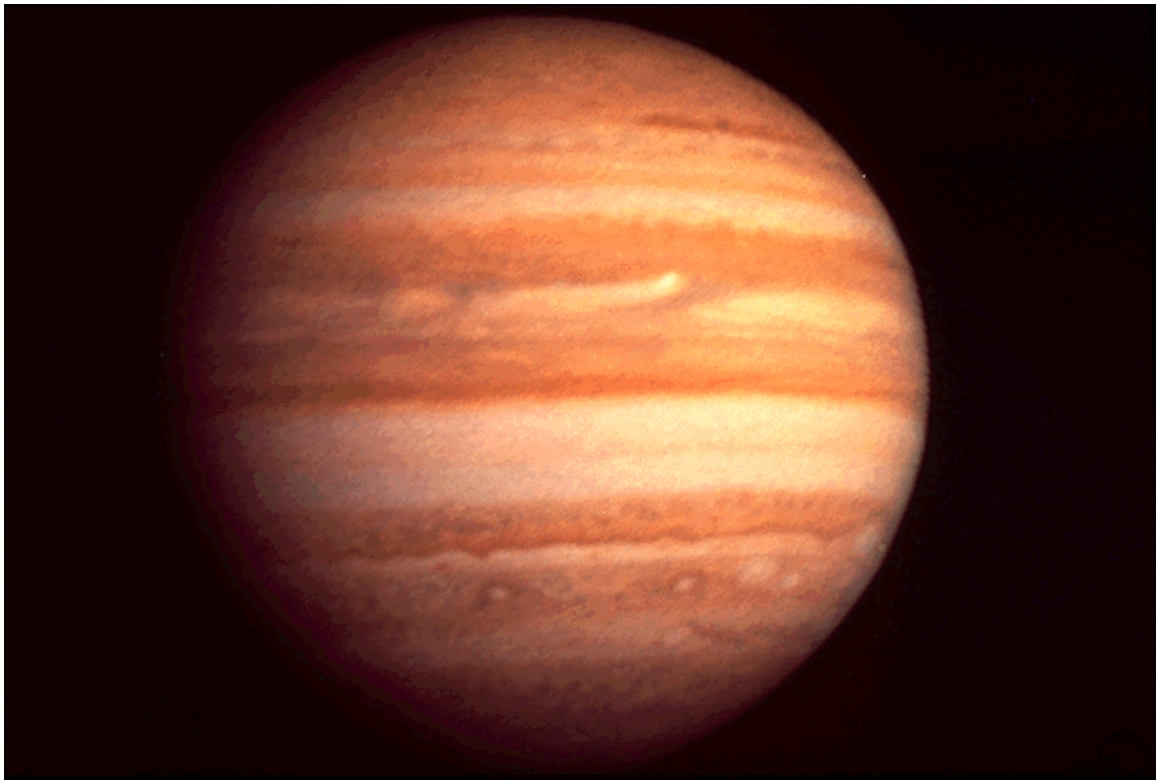
The *Pioneer 11* probe was launched on April 6, 1973 at 02:11:00 UTC, by the National Aeronautics and Space Administration from Space Launch Complex 36A at Cape Canaveral, Florida aboard an Atlas/Centaur launch vehicle. Twin probe, Pioneer 10, had previously launched a year before on March 3, 1972.

Pioneer 11 launching from Space Launch Complex 36A

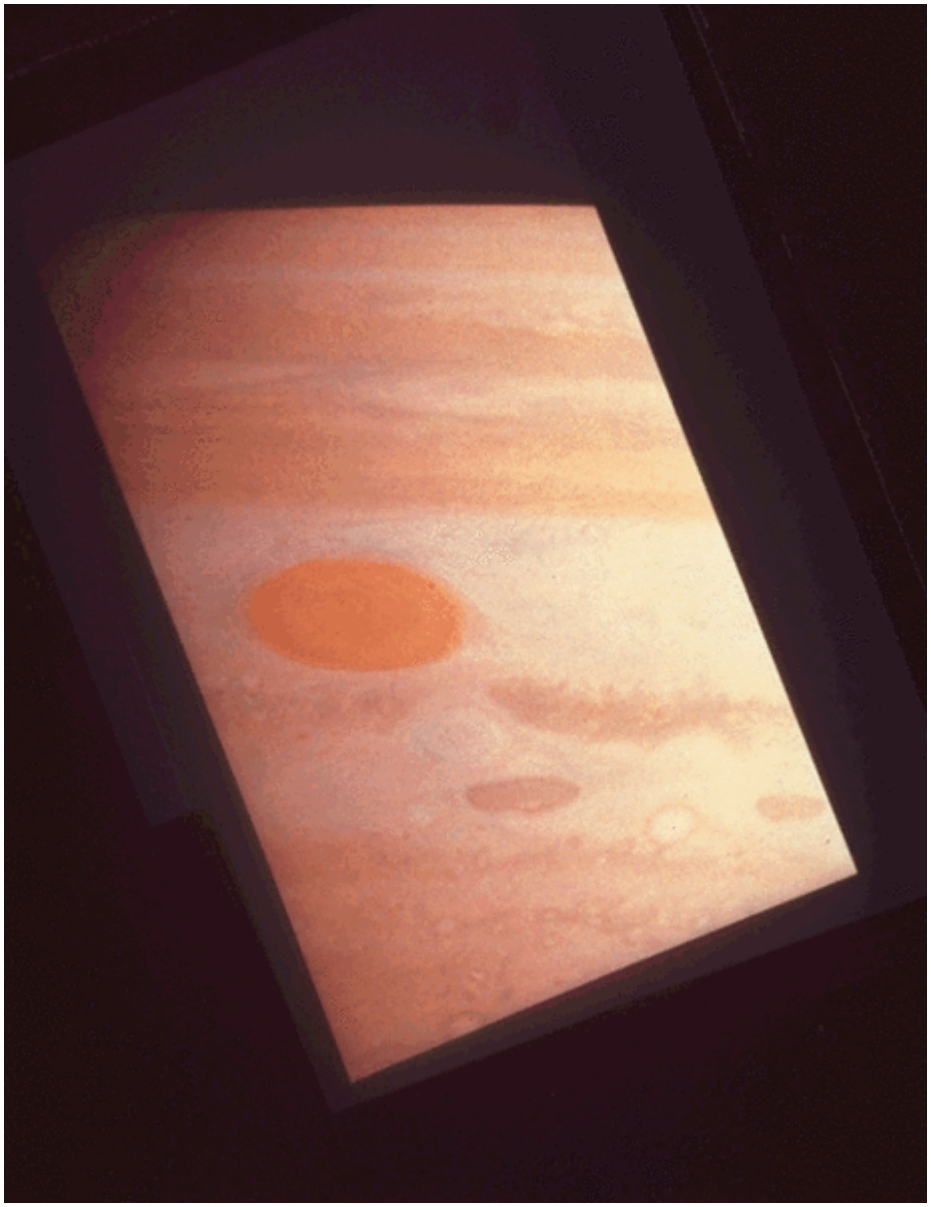
## Encounter with Jupiter

In November and December 1974, During its closest approach, December 2, 1974, *Pioneer 11* reached closest approach to Jupiter, passing 42,828 kilometers (26,612 miles) above the cloud tops. The probe obtained detailed images of the Great Red Spot, transmitted the first images of the immense polar regions, and determined the mass of Jupiter's moon Callisto. Utilizing the gravitational pull of Jupiter, a gravity assist was used to alter the trajectory of the probe, towards Saturn.

*Pioneer 11* Jupiter encounter

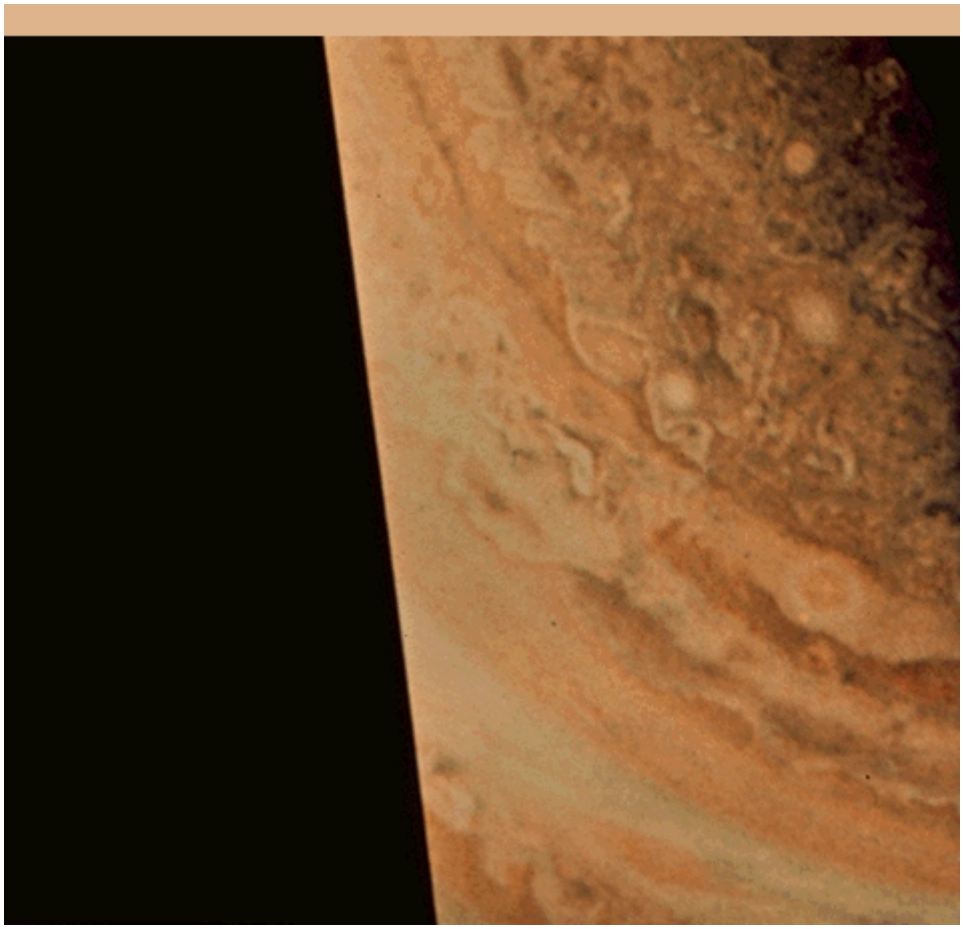


Approach on Jupiter

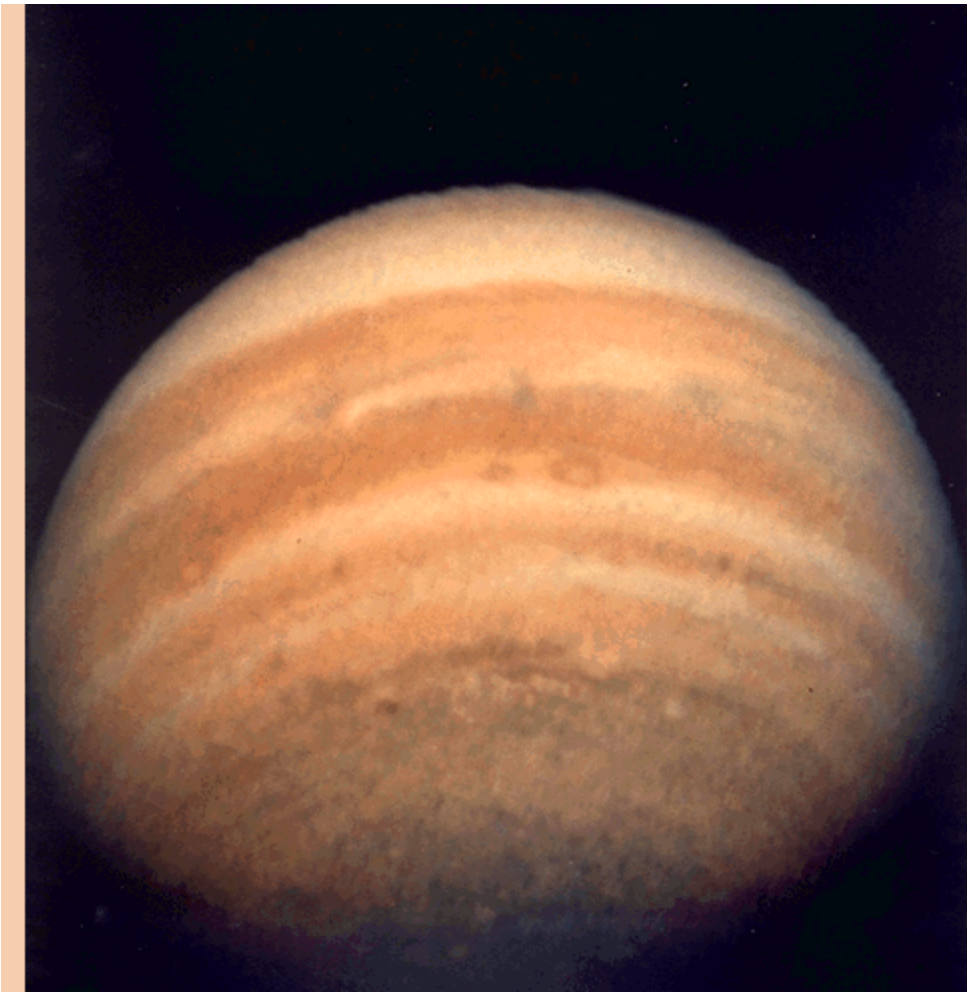


The Great Red Spot imaged by *Pioneer 11*

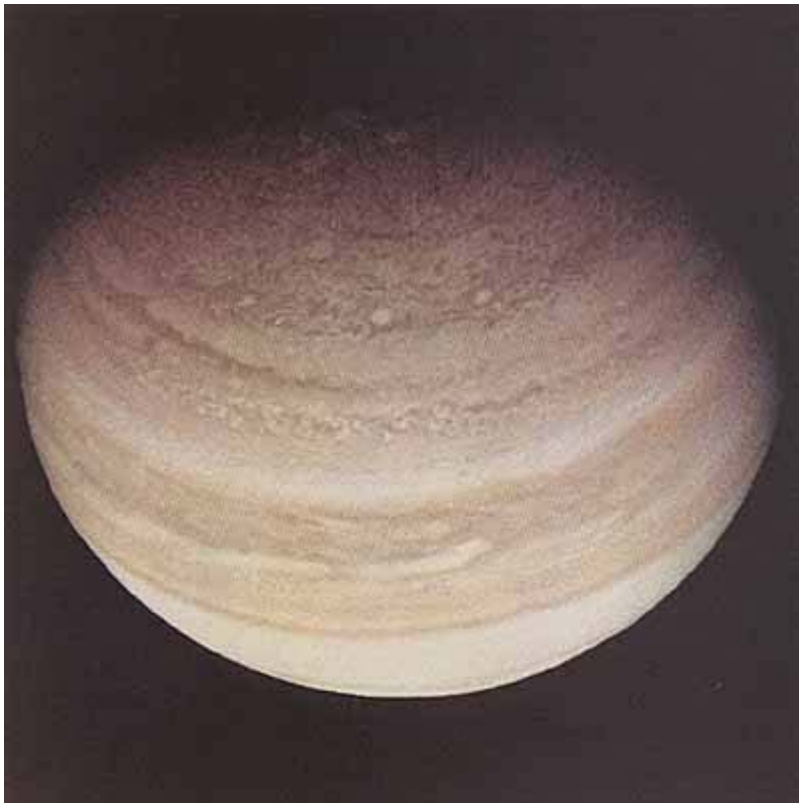
The Great Red Spot prior to closest approach



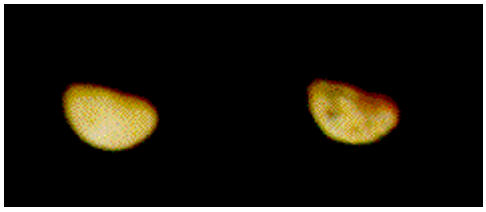
Cloud bands along the edge of Jupiter



Beginning polar gravity assist



Jupiter polar region from 1,079,000 km



Io imaged from 756,000 km.

## Saturn encounter

Pioneer 11 and Saturn rings on September 1, 1979 (artist's impression)

Pioneer 11 passed by Saturn on September 1, 1979, at a distance of 21,000 km from Saturn's cloud tops.

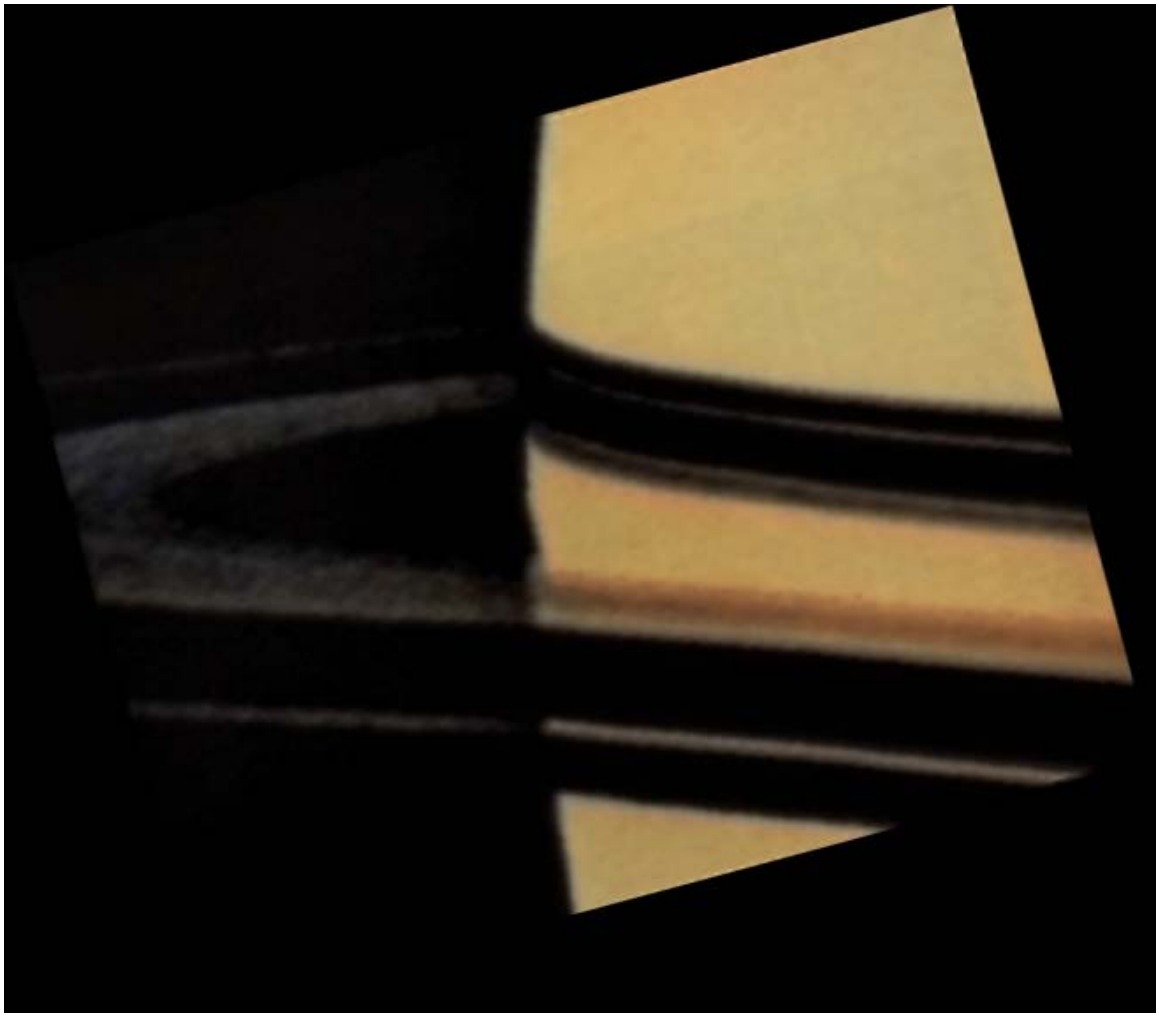
By this time Voyager 1 and Voyager 2 had already passed Jupiter and were also en route to Saturn, so it was decided to target Pioneer 11 to pass through the Saturn ring plane at the same position that the soon-to-come Voyager probe would use in order to test the route before Voyager arrived. If there were faint ring particles that could damage a probe in that area, mission planners felt it was better to learn about it via Pioneer. Thus, Pioneer 11 was acting as a "pioneer" in a true sense of the word; if danger was detected, then the Voyager probes could be rerouted further away from the rings, but missing the opportunity to visit Uranus and Neptune in the process.

Pioneer 11 imaged and nearly collided with one of Saturn's small moons, passing at a distance of no more than 2500 miles. The object was tentatively identified as Epimetheus, a moon discovered the previous day from Pioneer's imaging, and suspected from earlier observations by Earth-based telescopes. After the Voyager flybys, it became known that there are two similarly-sized moons (Epimetheus and Janus) in the same orbit, so there is some uncertainty about which one was the object of Pioneer's near-miss. Pioneer 11

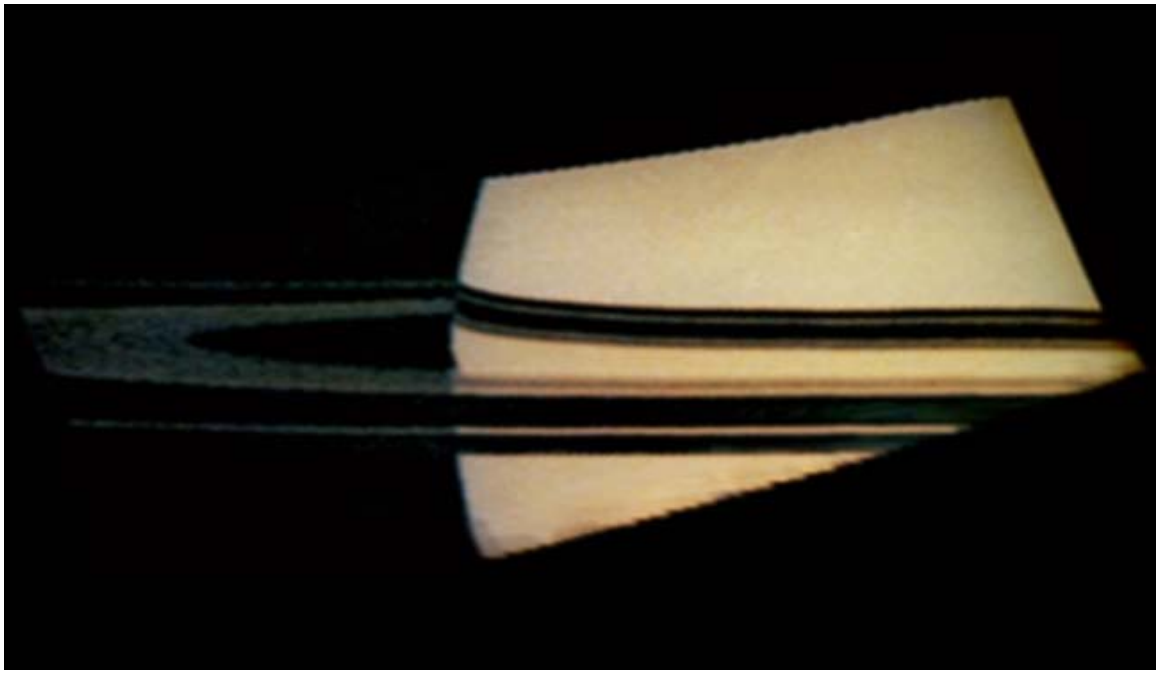
encountered Janus on September 1, 1979 at 14:52 UTC at a distance of 2500 km and Mimas at 16:20 UTC the same day at 103000 km.

Besides Epimetheus, instruments located another previously undiscovered small moon and an additional ring, charted Saturn's magnetosphere and magnetic field and found its planet-size moon, Titan, to be too cold for life. Hurtling underneath the ring plane, Pioneer 11 sent back amazing pictures of Saturn's rings. The rings, which normally seem bright when observed from Earth, appeared dark in the Pioneer pictures, and the dark gaps in the rings seen from Earth appeared as bright rings.

Pioneer 11 image of Saturn taken on 1979/08/26



Pioneer 11 image of Saturn taken on 1979/09/01.



Pioneer 11 image of Saturn taken on 1979/09/01

Outgoing Pioneer 11 image of Saturn taken on 1979/09/03

## 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 an anomalous, small Doppler frequency drift. The drift can be interpreted as being due to a constant acceleration of $(8.74 \pm 1.33) \times 10^{-10}$ m/s² directed towards the Sun. Although it is suspected that there is a systematic origin to the effect, none has been found. As a result, the nature of this anomaly has become of growing interest.

# Chapter 6

# 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<br>(33 years, 5 months, and 19 days ago) |
| **Launch vehicle** | Titan IIIE / Centaur |
| **Launch site** | Space Launch Complex 41<br>Cape Canaveral Air Force Station |
| **Mission duration** | In progress (Interstellar mission) |

| | |
|---|---|
| | (32 years, 1 month, and 20 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 19 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.

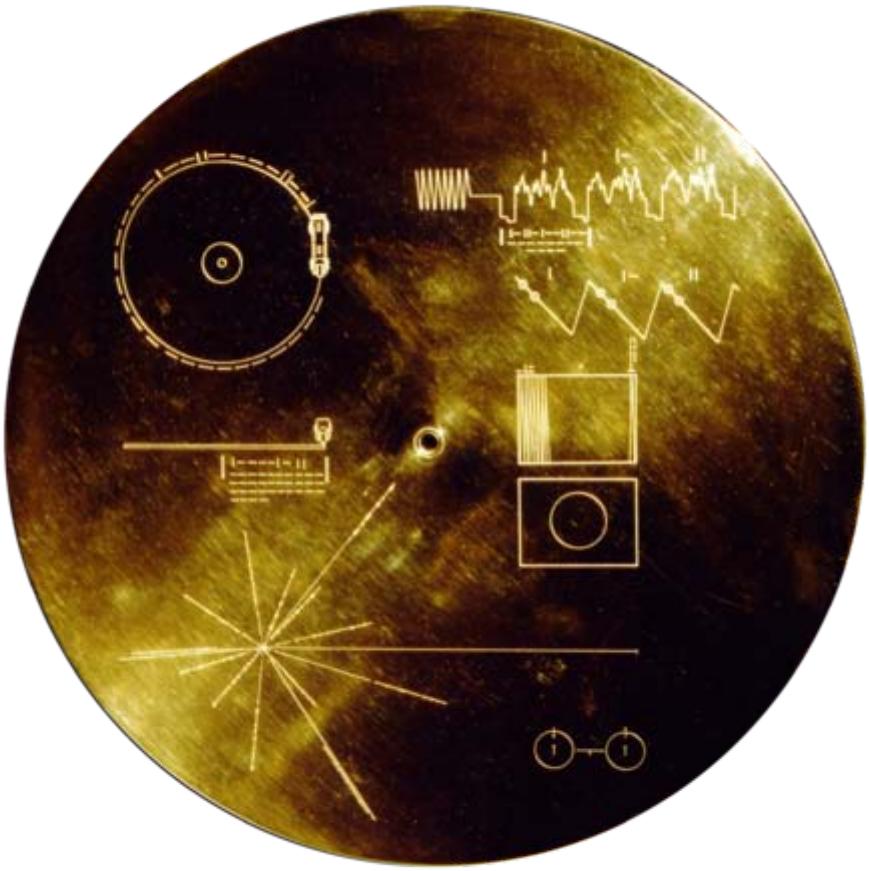
# Mission background

## 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.

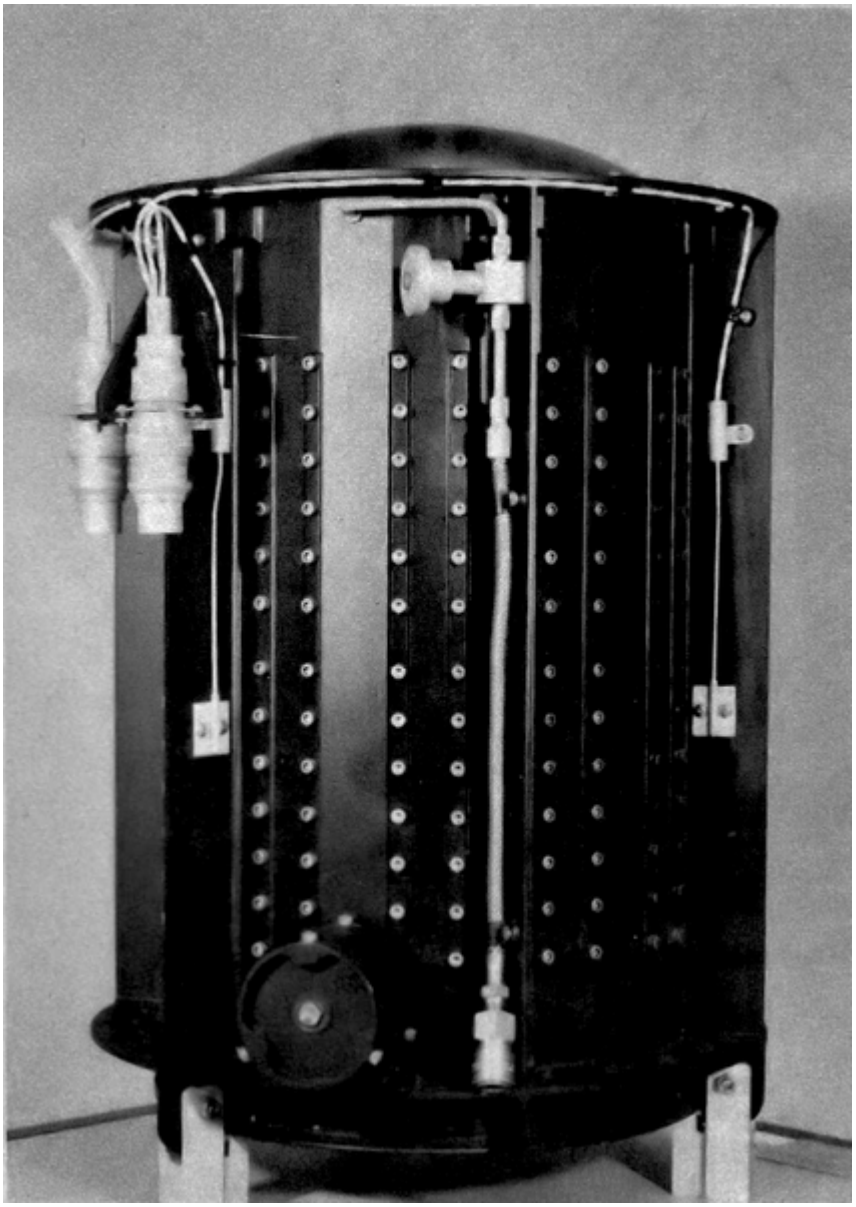
## Spacecraft design

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.<br>**Filters**<br>**Narrow Angle Camera Filters**<br>**Wide Angle Camera Filters**<br>• **Principal investigator:** Bradford Smith / University of Arizona (PDS/PRN website)<br>• **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.<br>• **Principal investigator:** G. Tyler / Stanford University PDS/PRN overview<br>• **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.<br>• **Principal investigator:** Rudolf Hanel / NASA Goddard Space Flight Center (PDS/PRN website)<br>• **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.<br>• **Principal investigator:** A. Broadfoot / University of Southern California (PDS/PRN website)<br>• **Data:** PDS/PRN data catalog |

**Narrow Angle Camera Filters**

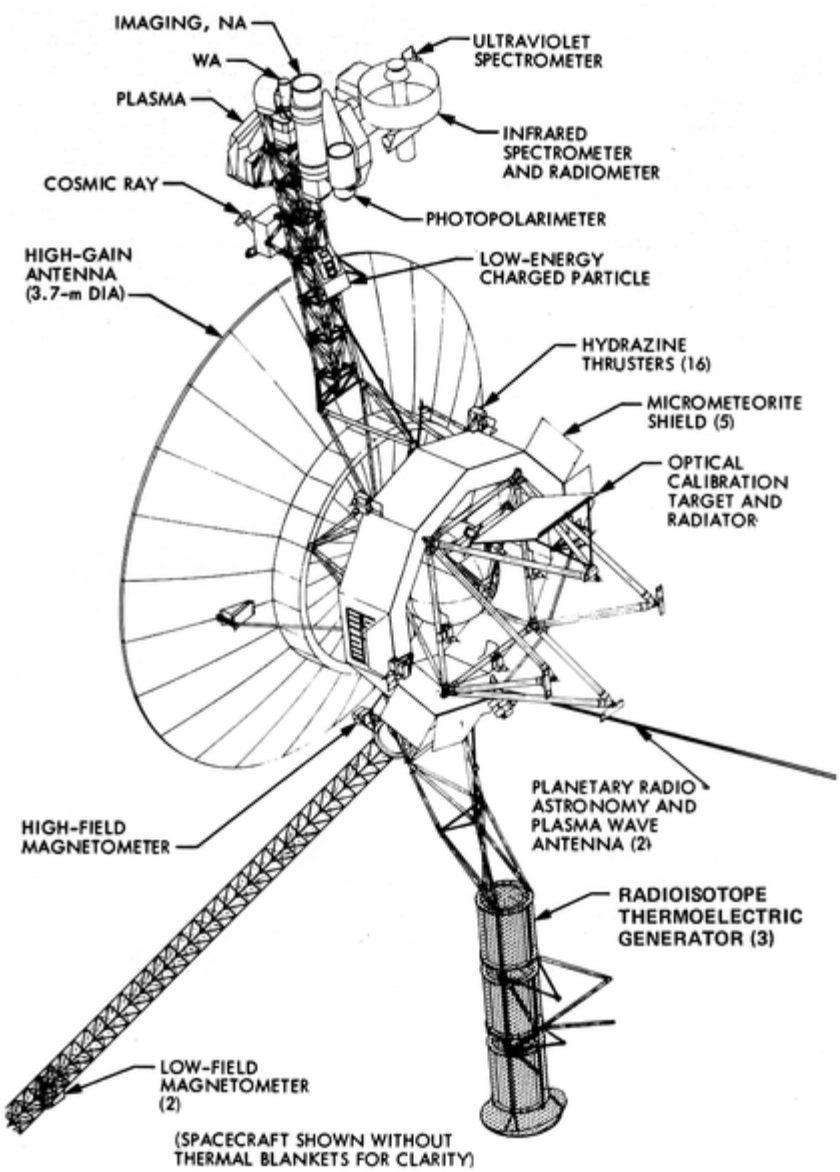
| Name | Wavelength | Spectrum | Sensitivity |
|---|---|---|---|
| Clear | 280 nm - 640 nm | | |
| UV | 280 nm - 370 nm | | |
| Violet | 350 nm - 450 nm | | |
| Blue | 430 nm - 530 nm | | |
| ' | ' | | ' |
| Green | 530 nm - 640 nm | | |
| ' | ' | | ' |
| Orange | 590 nm - 640 nm | | |
| ' | ' | | '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

**Wide Angle Camera Filters**

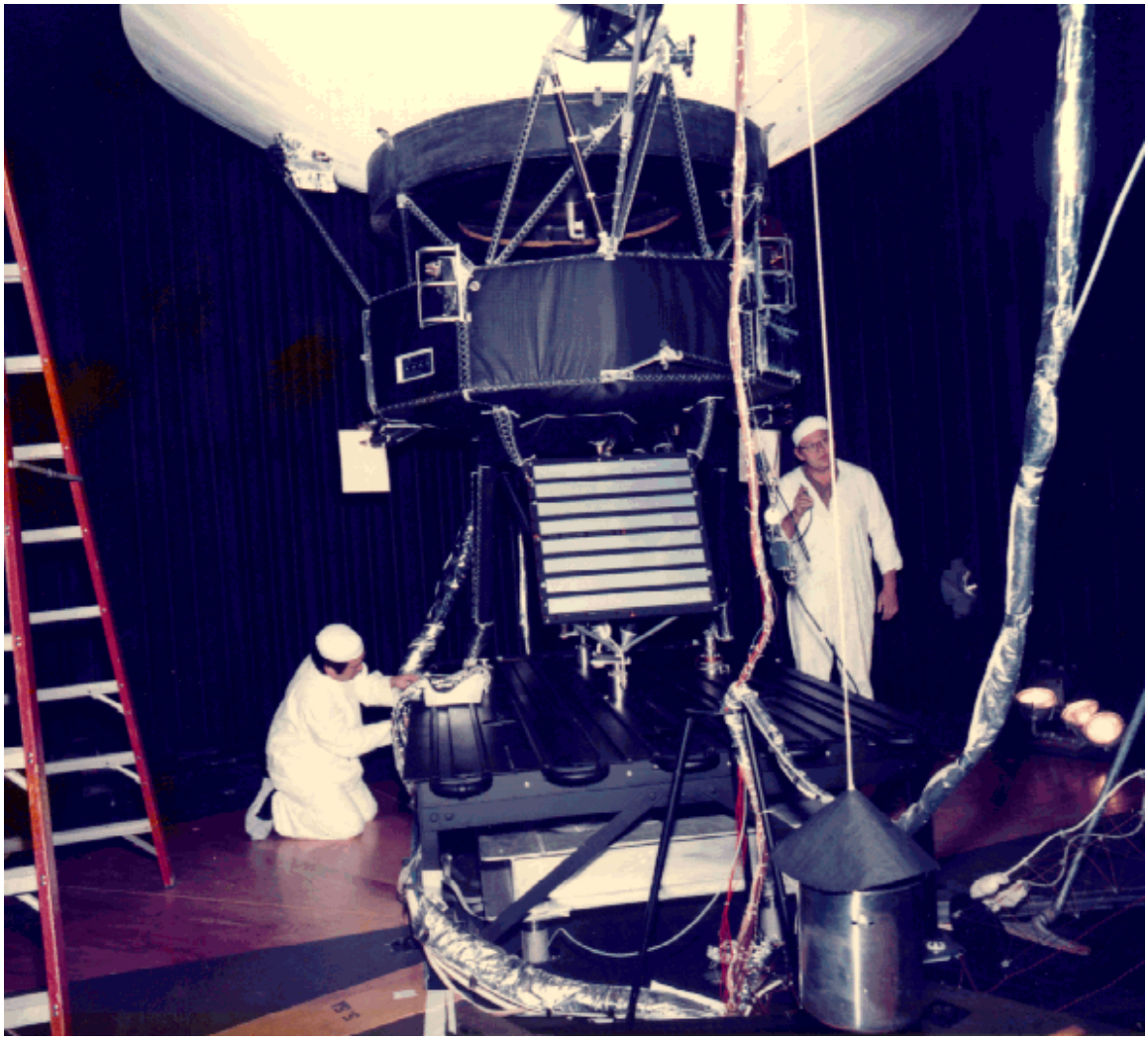
| Name | Wavelength | Spectrum | Sensitivity |
|---|---|---|---|
| Clear | 280 nm - 640 nm | | |
| ' | ' | | ' |
| Violet | 350 nm - 450 nm | | |
| Blue | 430 nm - 530 nm | | |
| $CH_4$-U | 536 nm - 546 nm | | |
| Green | 530 nm - 640 nm | | |
| Na-D | 588 nm - 590 nm | | |
| Orange | 590 nm - 640 nm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

| | | |
|---|---|---|
| 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.<br>• **Principal investigator:** Norman Ness / NASA Goddard Space Flight Center (website)<br>• **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.<br>• **Principal investigator:** John Richardson / MIT (website)<br>• **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.<br>• **Principal investigator:** Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website)<br>• **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.<br>• **Principal investigator:** Edward Stone / CalTech / NASA Goddard Space Flight Center (website)<br>• **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.<br>• **Principal investigator:** James Warwick / University of Colorado<br>• **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.<br>• **Principal investigator:** Arthur Lane / JPL (PDS/PRN website)<br>• **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.<br>• **Principal investigator:** Donald Gurnett / University of Iowa (website)<br>• **Data:** PDS/PPI data catalog, NSSDC data archive |

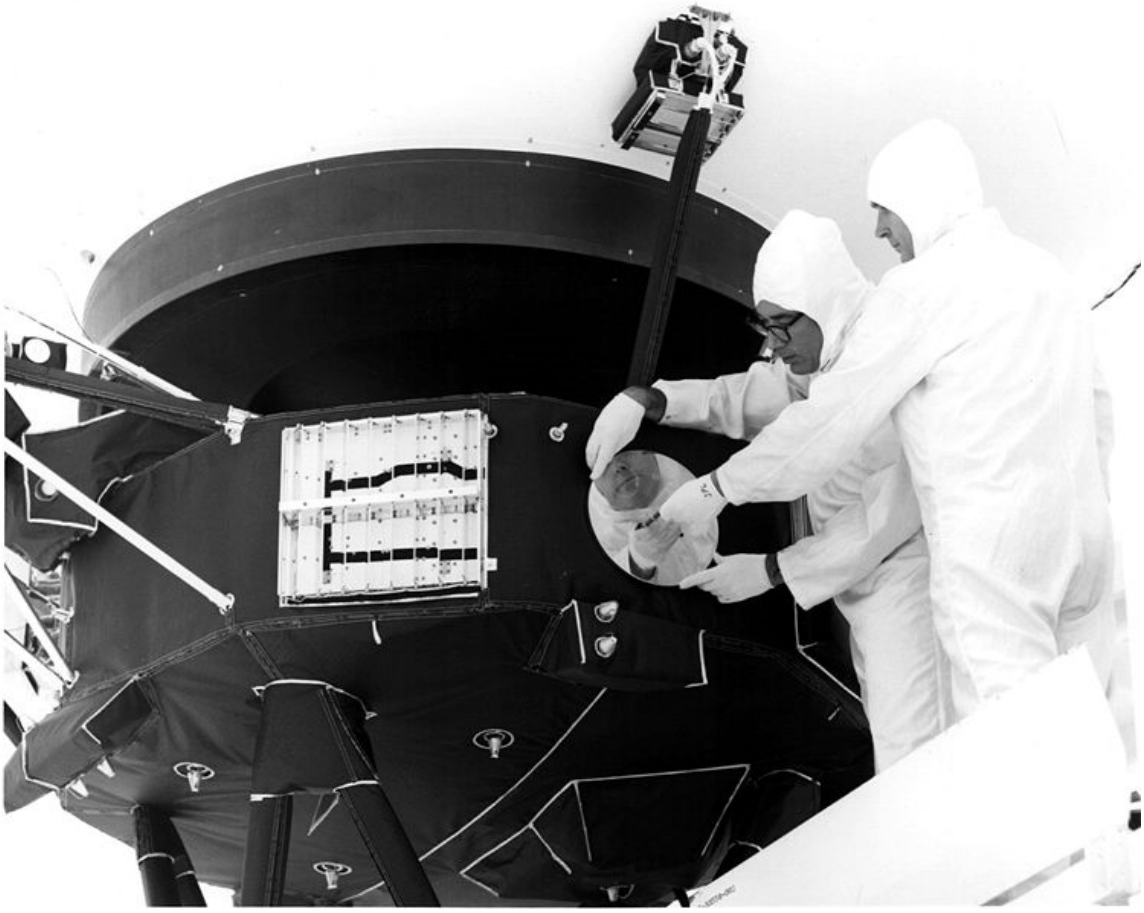
## Images of the spacecraft




*Voyager* spacecraft diagram



*Voyager 1* in a space simulator chamber



Gold-Plated Record is attached to *Voyager 1*

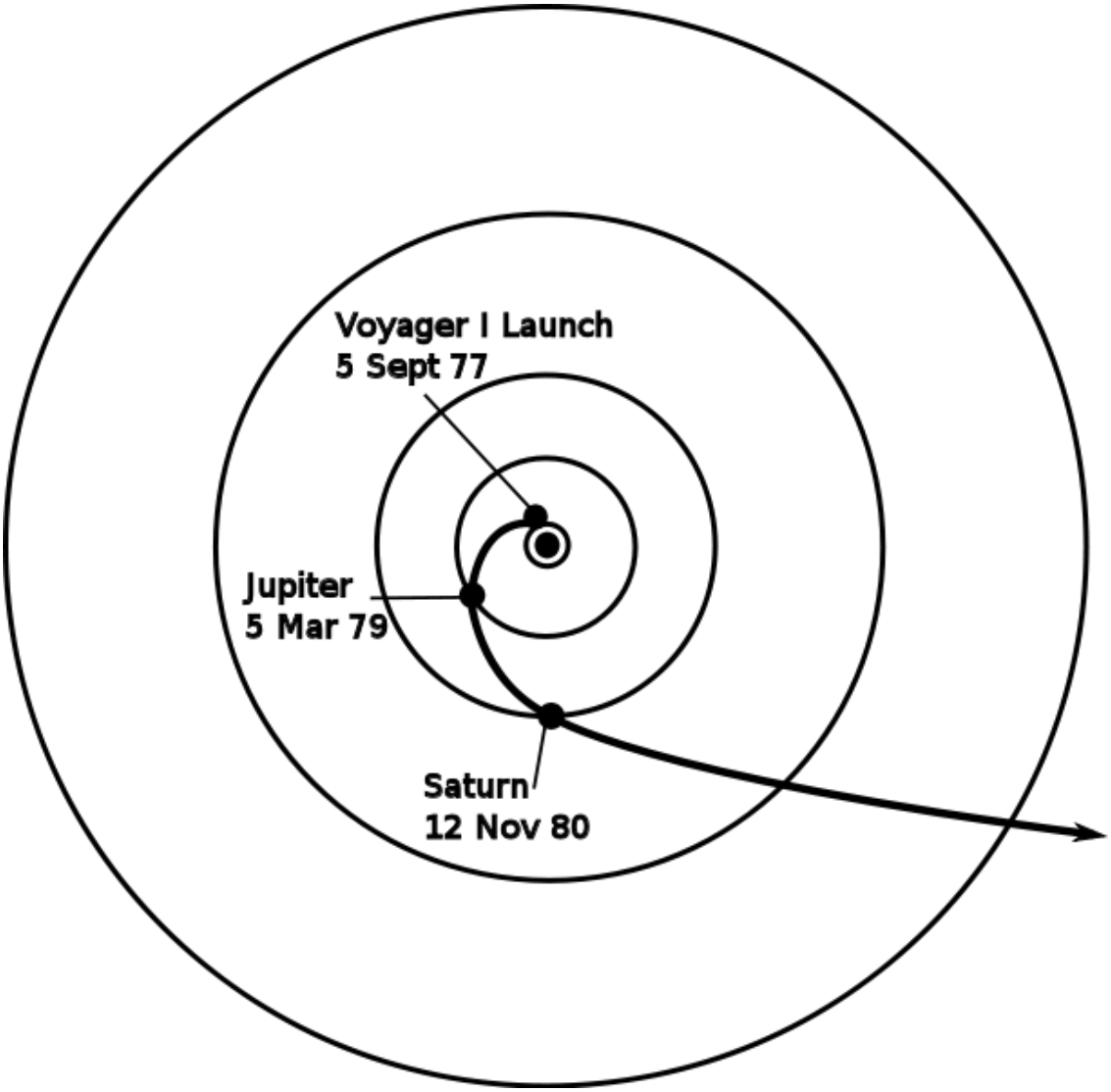
*Voyager 1* awaiting payload entry into a Titan/Centaur-6 rocket

# 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

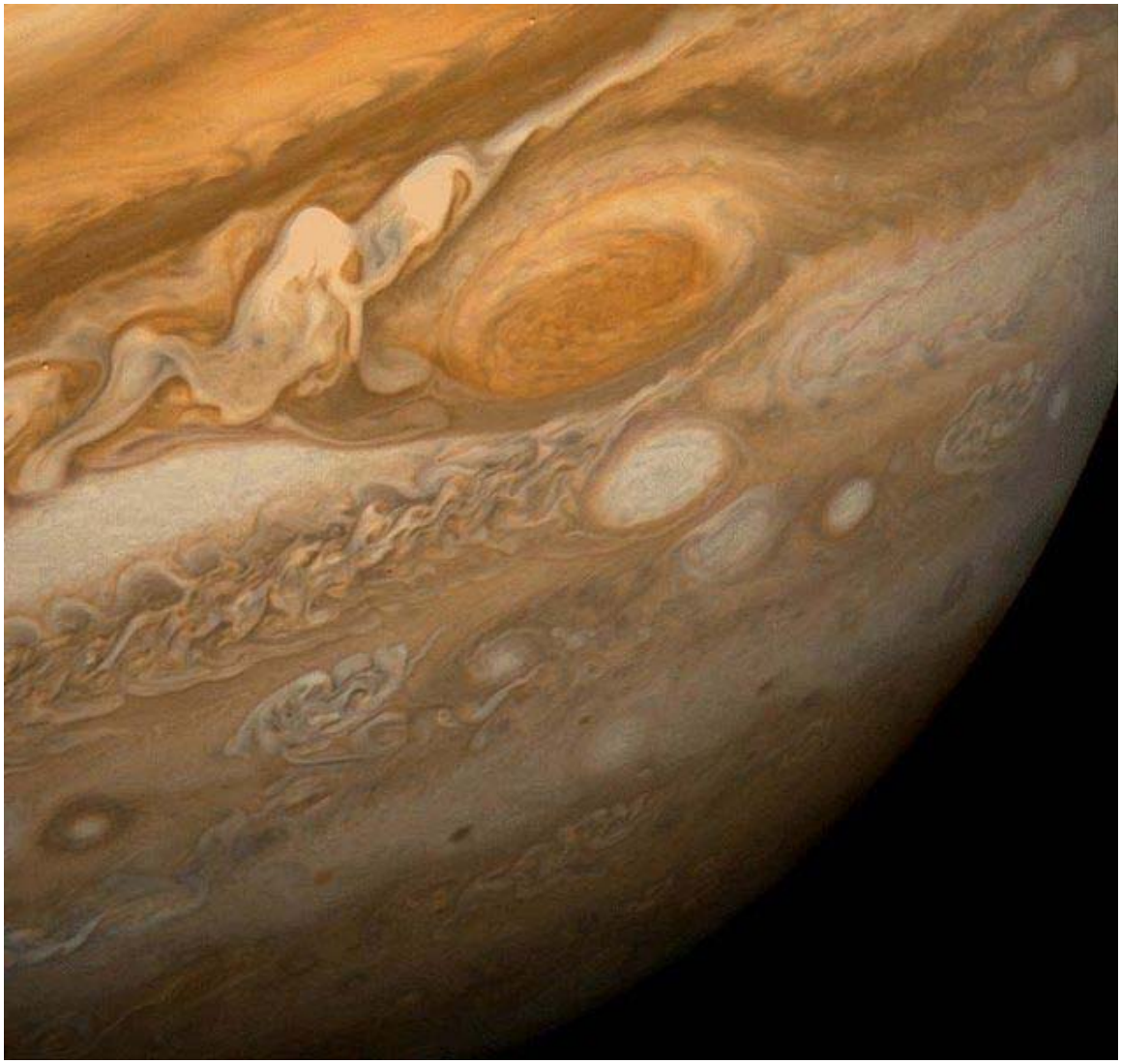



Trajectory of *Voyager 1* primary mission

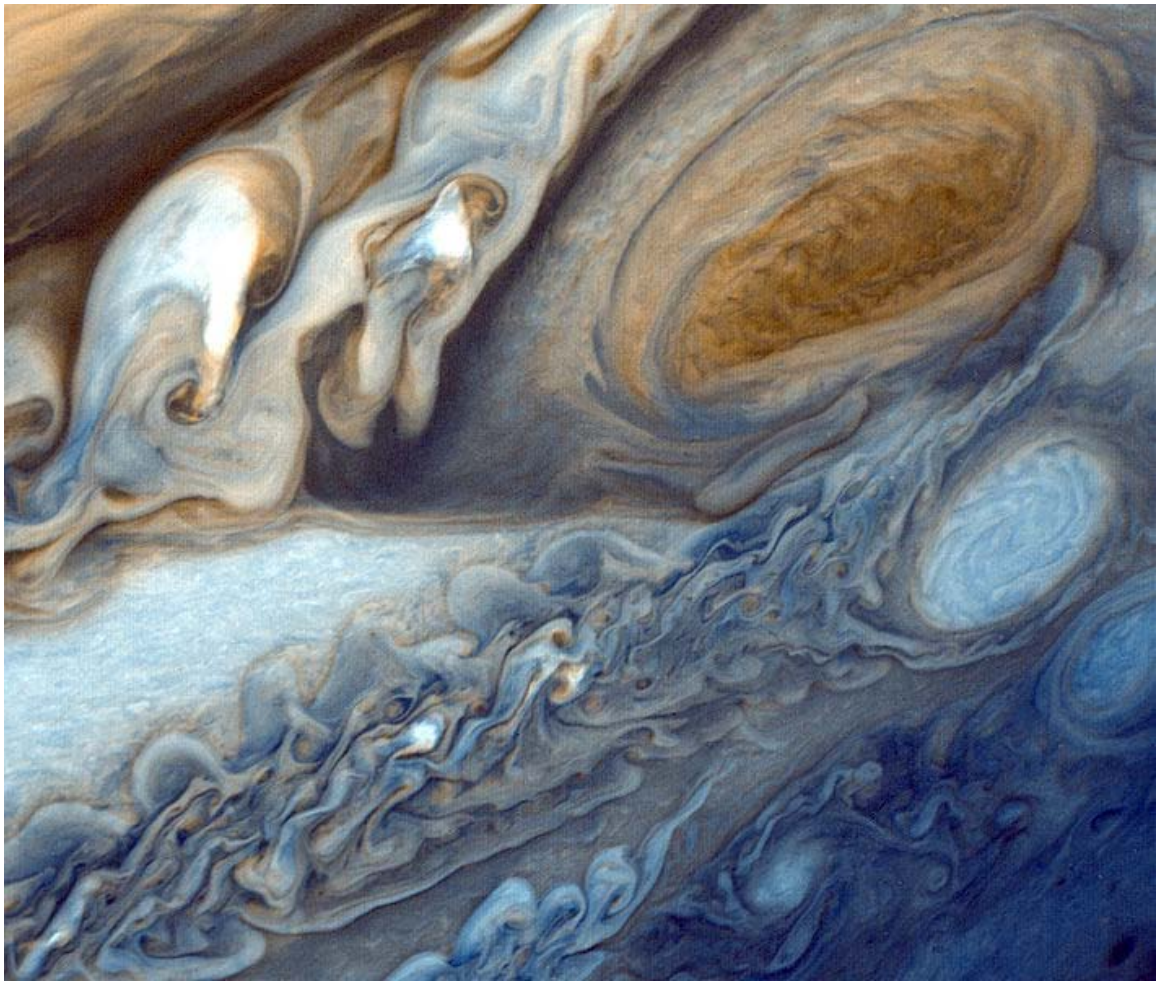
## Encounter with Jupiter

*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*.

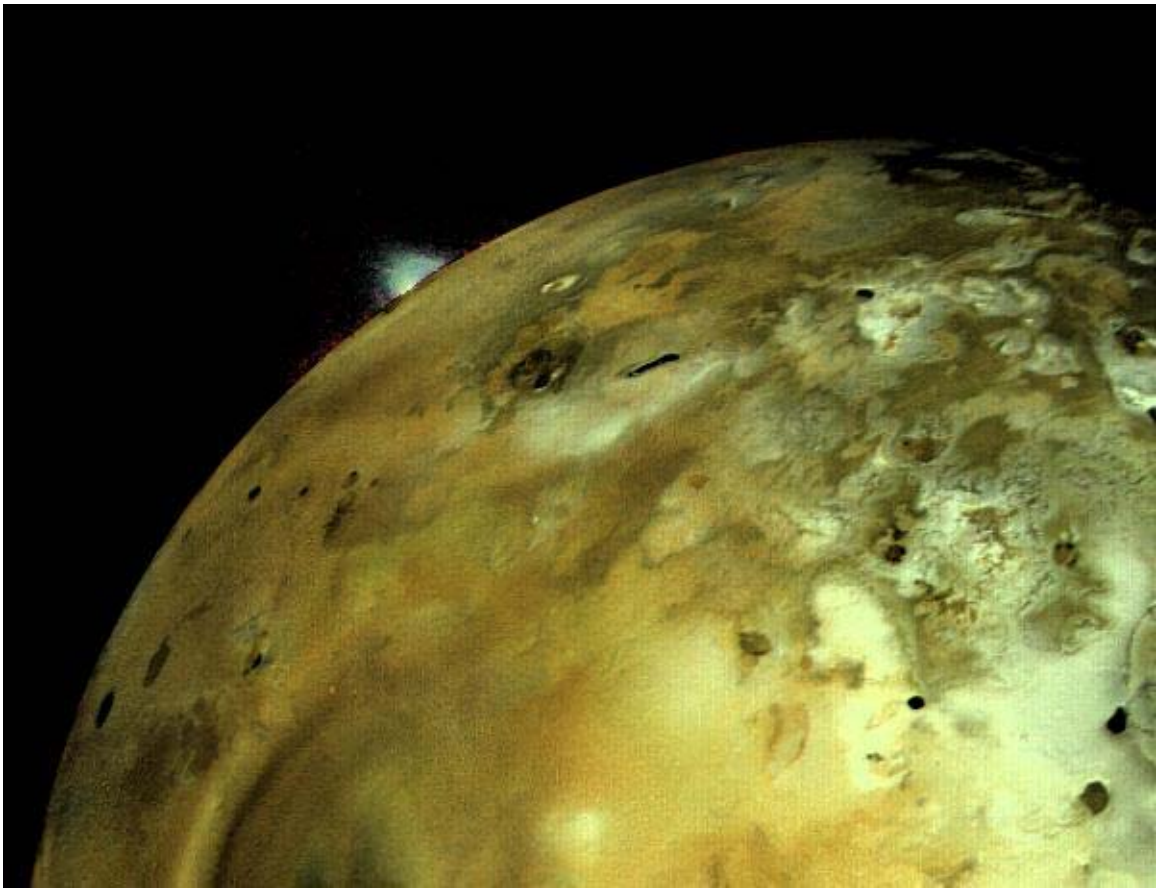


The Great Red Spot as seen from *Voyager 1*



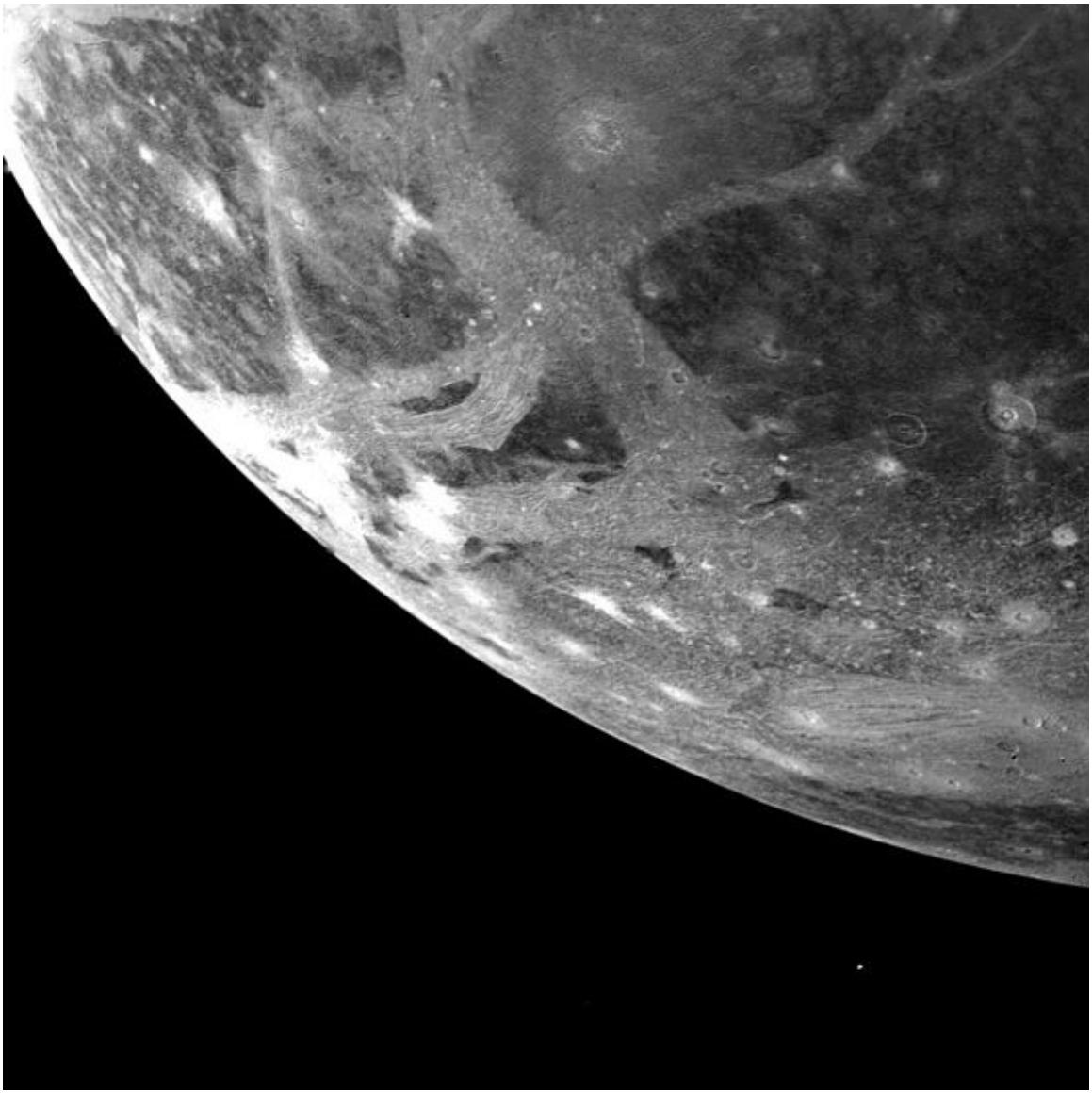
False color detail of Jupiter's atmosphere

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

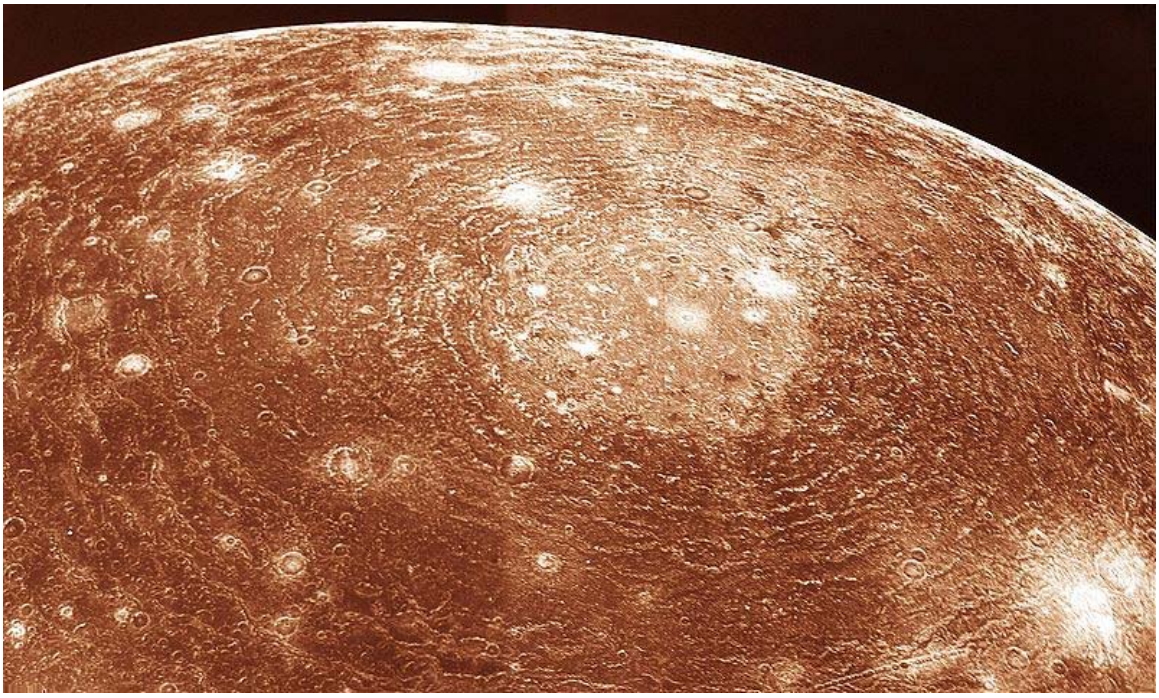


Volcanic eruption on Io photographed from Voyager 1.

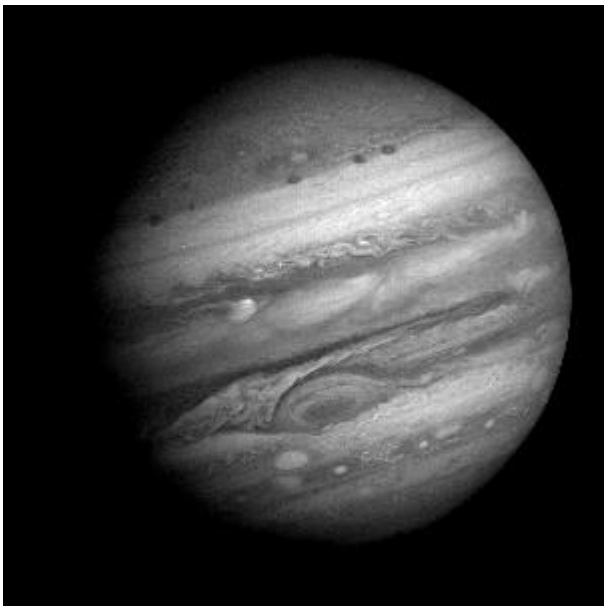
Europa as seen from *Voyager 1* at a distance of 2.8 million km



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



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



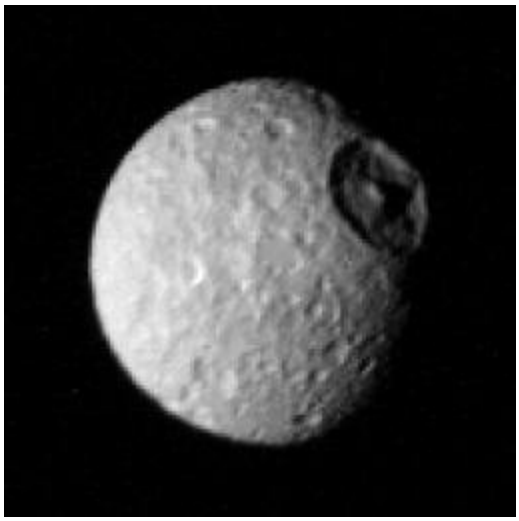
## Encounter with Saturn

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.

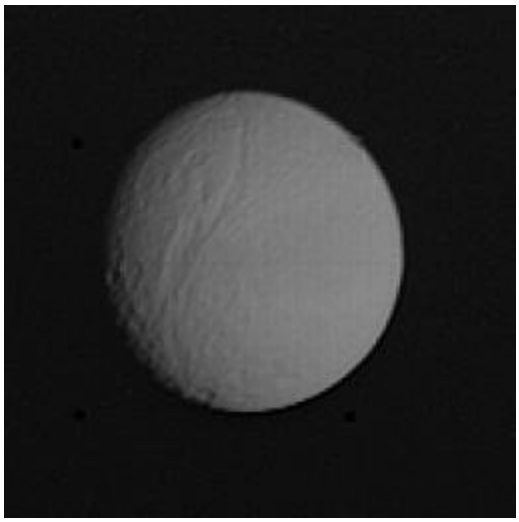
Because Pioneer 11 had one year earlier detected a thick, gaseous atmosphere over Titan, the *Voyager* space probes' controllers at the Jet Propulsion Laboratory elected for *Voyager 1* to make a close approach of Titan, and of necessity end its Grand Tour there.

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.

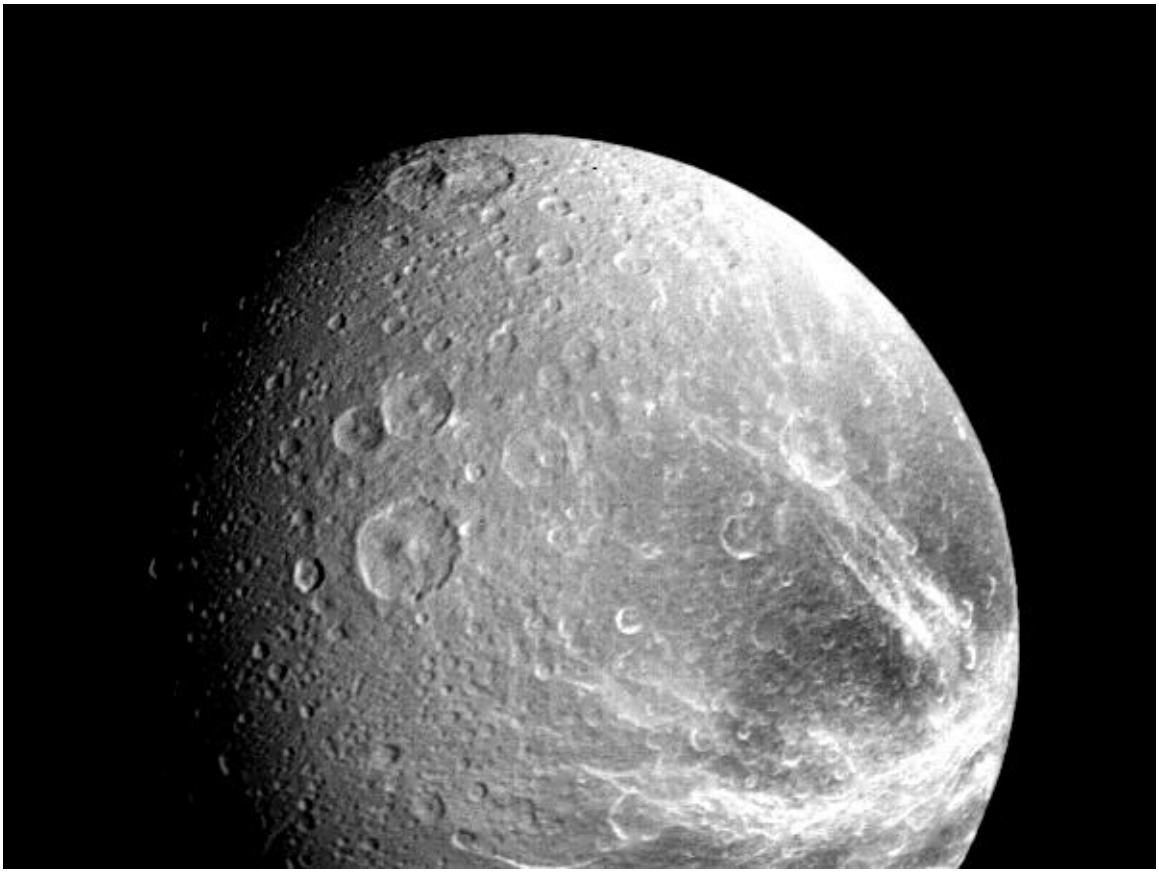
Saturn from 5.3 million km, four days after its closest approach



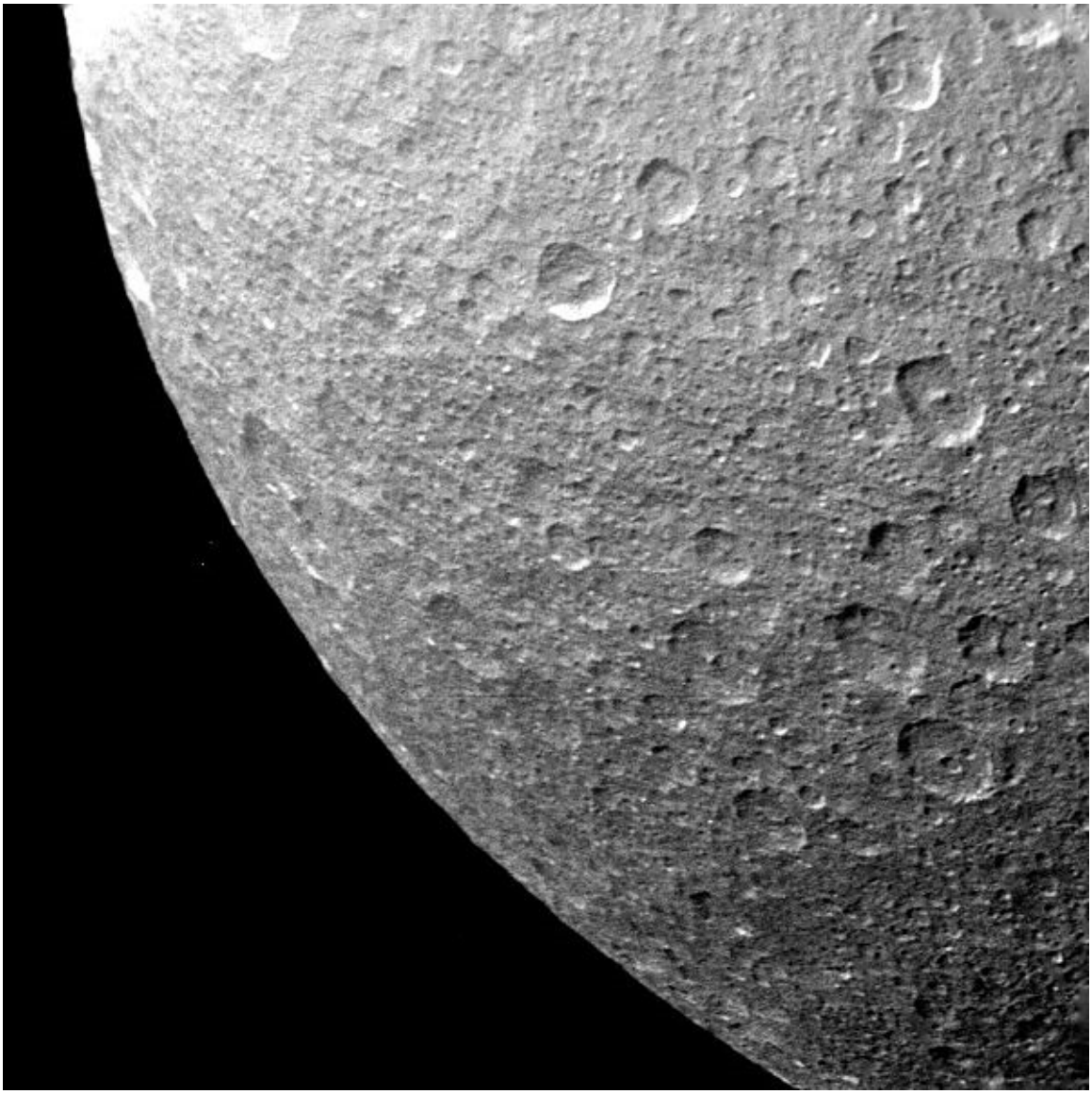
Mimas at a range of 425,000 km from *Voyager 1*



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

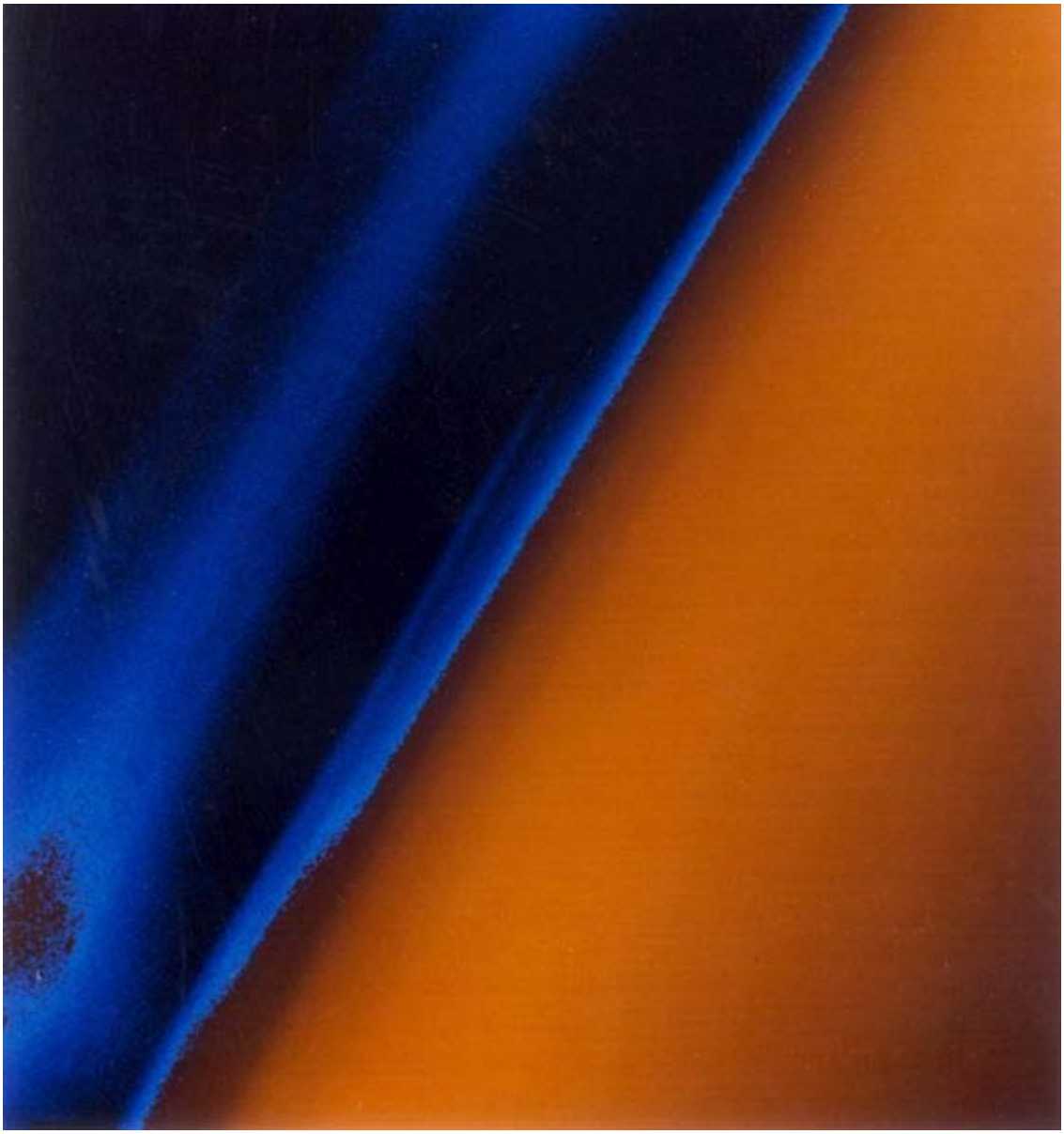


Fractured terrain on Dione



Impact craters on the surface of Rhea appear similar to Mercury

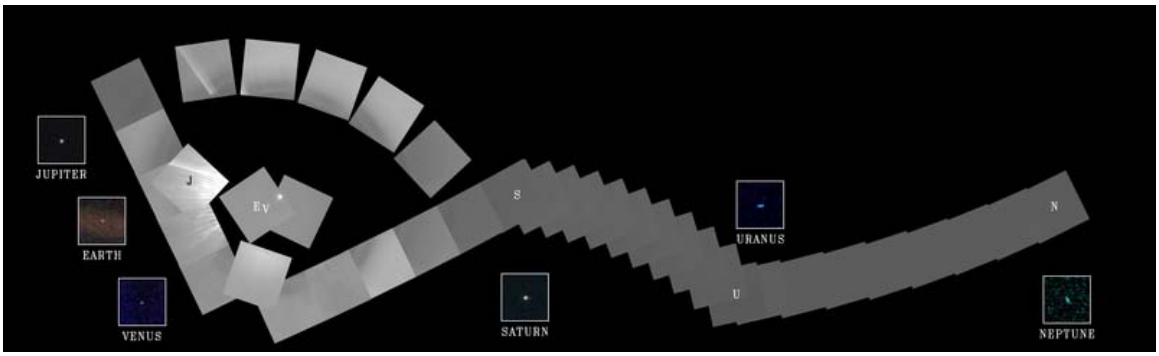
Titan's thick haze layer is shown in this enhanced *Voyager 1* image



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.

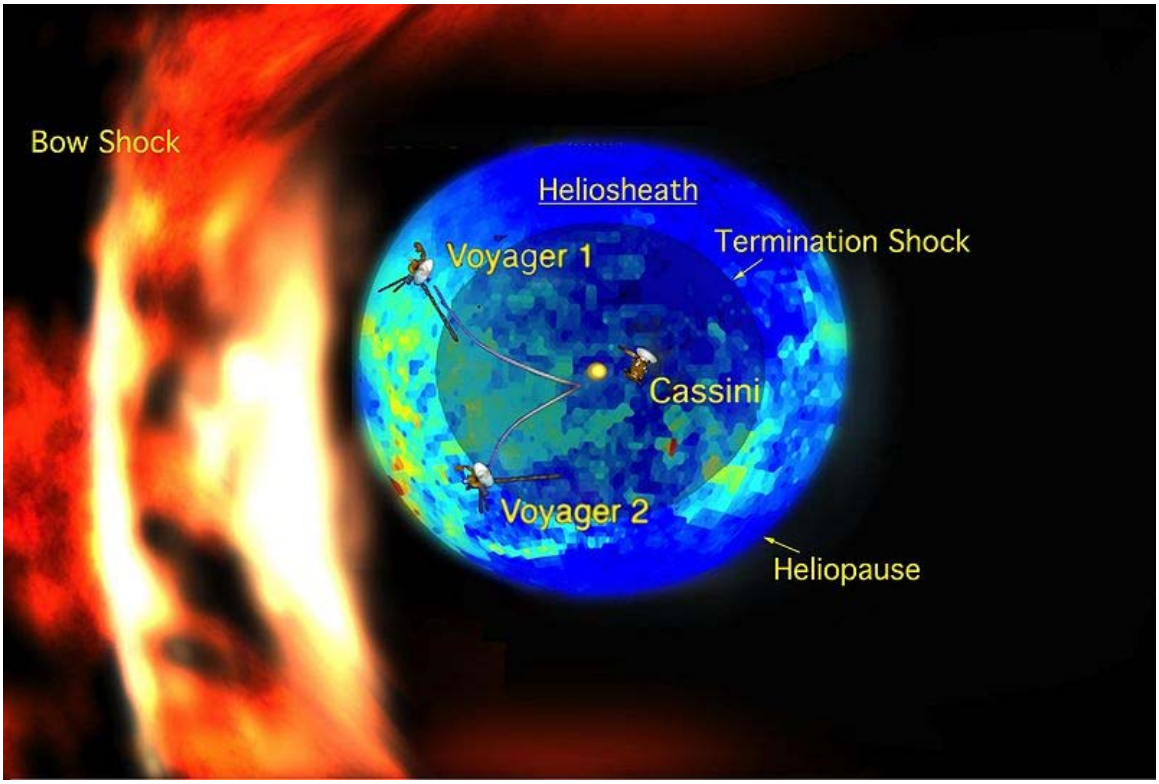
On November 17, 1998, *Voyager 1* overtook *Pioneer 10* as the most distant man-made object from Earth, at a distance of 69.419 AU. It is currently the most distant functioning

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.

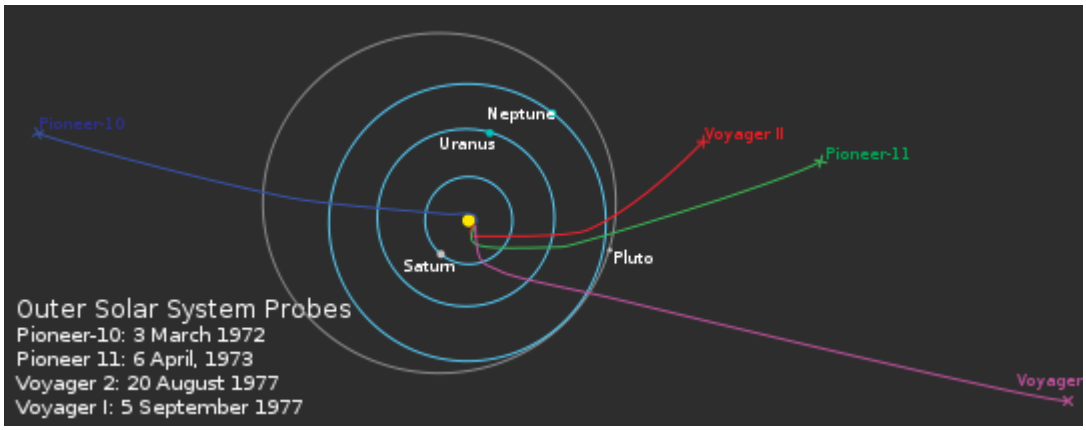
Scientists at the Johns Hopkins University Applied Physics Laboratory believe that *Voyager 1* entered the termination shock in February 2003. Some other scientists have expressed doubt, discussed in the journal *Nature* of November 6, 2003. In a scientific session at the American Geophysical Union meeting 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 22th, 2011**, *Voyager 1* was about 116.257AU (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 3.599 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.

*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.

As of **February 22th 2011** the spacecraft is at 12.07° declination and 17.182 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

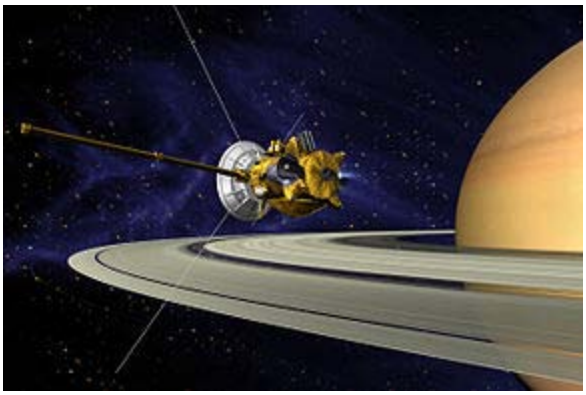
On **November 19, 2015**, *Voyager 1* is projected to be approximately 133.15 Astronomical Units from the Sun.

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 7

# Cassini–Huygens

**Cassini–Huygens**



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

| | |
|---|---|
| **Operator** | NASA / ESA / ASI |
| **Mission type** | Flyby, orbiter, lander |
| **Flyby of** | Venus, Moon, Earth, Masursky, Jupiter, Saturn's moons |
| **Satellite of** | Saturn |
| **Orbital insertion date** | 2004-07-01 02:48:00 UTC |
| **Launch date** | 1997-10-15 08:43:00 UTC<br>(13 years, 4 months, and 9 days ago) |
| **Launch vehicle** | Titan IV-B / Centaur |
| **Launch site** | Space Launch Complex 40<br>Cape Canaveral Air Force Station |

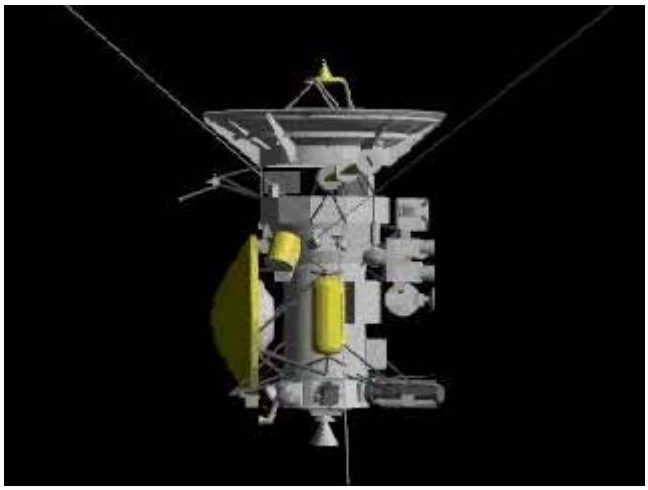
| | |
|---|---|
| **Mission duration** | In Progress (Solstice)<br>(6 years, 7 months, and 23 days elapsed)<br>Venus 1st flyby<br>*(completed 1998-04-26)*<br>Venus 2nd flyby<br>*(completed 1999-06-24)*<br>Moon flyby<br>*(completed 1999-08-18)*<br>Earth flyby<br>*(completed 1999-08-18)*<br>Masursky flyby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

***Cassini–Huygens*** is a joint NASA/ESA/ASI robotic spacecraft mission currently studying the planet Saturn and its many natural satellites. The spacecraft consists of two main elements: the NASA-designed and -constructed *Cassini* orbiter, named for the Italian-French astronomer Giovanni Domenico Cassini, and the ESA-developed *Huygens* probe, named for the Dutch astronomer, mathematician and physicist Christiaan Huygens. The complete *Cassini* space probe was launched on October 15, 1997, and after a long interplanetary voyage it entered into orbit around Saturn on July 1, 2004. On December 25, 2004, the *Huygens* probe was separated from the orbiter at approximately 02:00 UTC. It reached Saturn's moon Titan on January 14, 2005, when it descended into Titan's atmosphere, and downward to the surface, radioing scientific information back to the Earth by telemetry. This was the first landing ever accomplished in the outer solar system. On April 18, 2008, NASA announced a two-year extension of the funding for

ground operations of this mission, at which point it was renamed to **Cassini Equinox Mission**. This was again extended in February 2010 with the mission now continuing until 2017. *Cassini* is the fourth space probe to visit Saturn and the first to enter orbit.

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

# Objectives



Satellite

*Cassini* has seven primary objectives:

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

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

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

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

## History

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

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

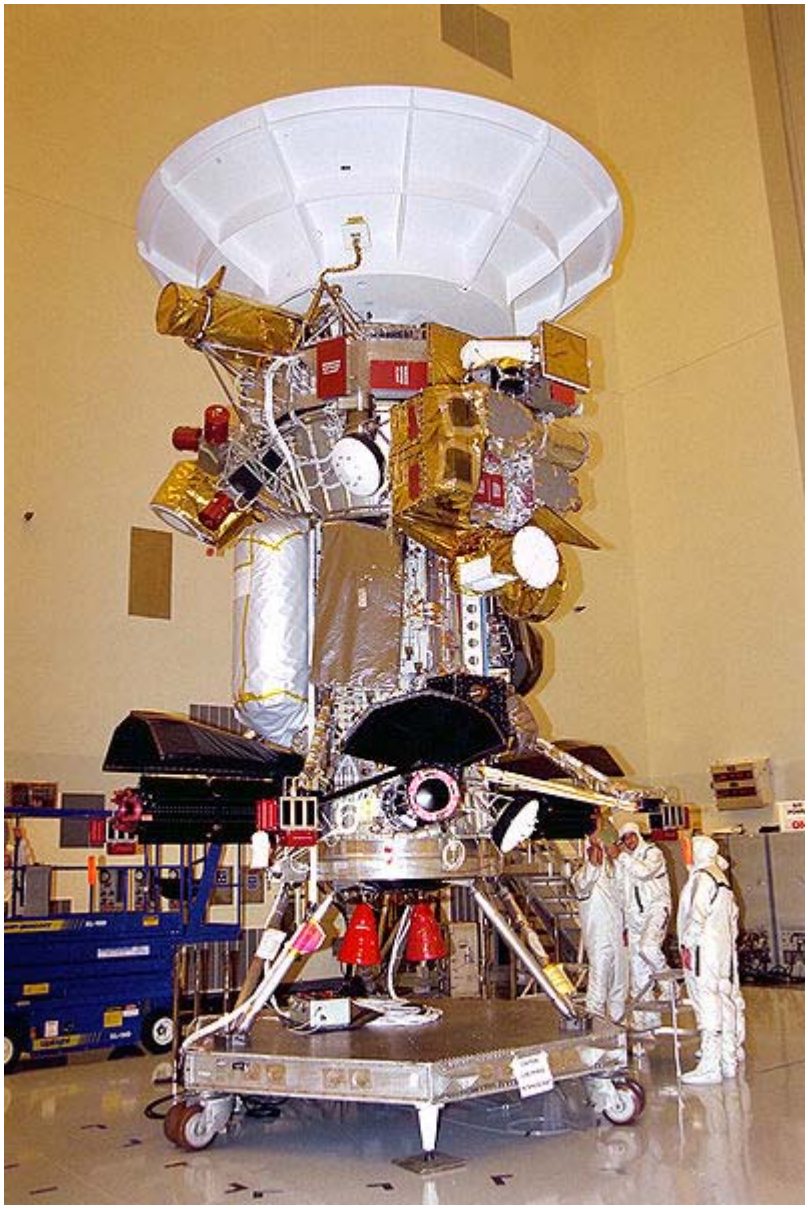
American astronaut Sally Ride, in her influential 1987 report "NASA Leadership and America's Future in Space", also examined and approved of the *Cassini* mission.

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

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

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

## Spacecraft design



*Cassini* assembly

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

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

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

## Instruments

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

*Cassini* Plasma Spectrometer (CAPS)

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

Cosmic Dust Analyzer (CDA)

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

Composite Infrared Spectrometer (CIRS)

The CIRS is a remote sensing instrument that measures the infrared waves coming from objects to learn about their temperatures, thermal properties, and

compositions. Throughout the Cassini–Huygens mission, the CIRS will measure infrared emissions from atmospheres, rings and surfaces in the vast Saturn system. It will map the atmosphere of Saturn in three dimensions to determine temperature and pressure profiles with altitude, gas composition, and the distribution of aerosols and clouds. It will also measure thermal characteristics and the composition of satellite surfaces and rings.

Ion and Neutral Mass Spectrometer (INMS)

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

Imaging Science Subsystem (ISS)

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

Dual Technique Magnetometer (MAG)

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

Magnetospheric Imaging Instrument (MIMI)

The MIMI is both a direct and remote sensing instrument that produces images and other data about the particles trapped in Saturn's huge magnetic field, or magnetosphere. This information will be used to study the overall configuration and dynamics of the magnetosphere and its interactions with the solar wind, Saturn's atmosphere, Titan, rings, and icy satellites.

Radar

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

Radio and Plasma Wave Science instrument (RPWS)

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

Radio Science Subsystem (RSS)

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

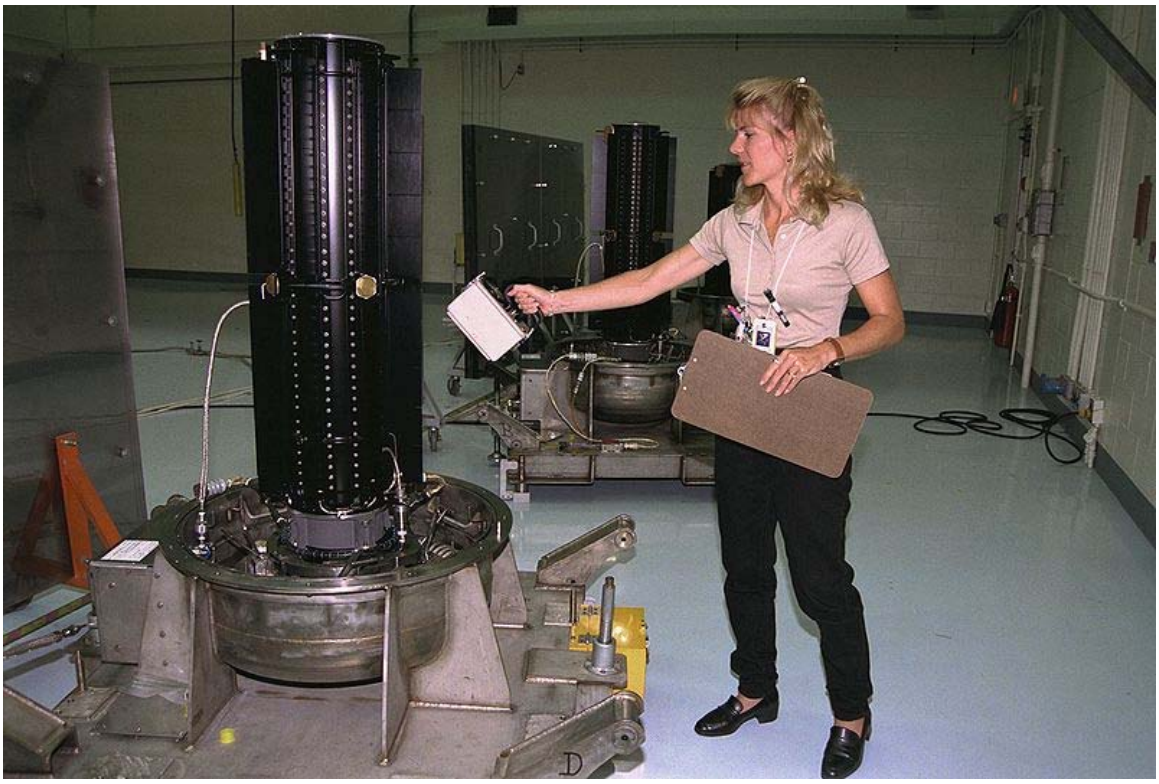
Ultraviolet Imaging Spectrograph (UVIS)

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

Visible and Infrared Mapping Spectrometer (VIMS)

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

## Plutonium power source



Inspection of *Cassini* spacecraft RTGs before launch

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

To gain interplanetary momentum while already in flight, the trajectory of the *Cassini* mission included several gravitational slingshot maneuvers: two fly-by passes of Venus, one more of the Earth, and then one of the planet Jupiter. The terrestrial fly-by was the final instance when the *Cassini* space probe posed any conceivable danger to human beings. This occurred successfully, with hundreds of miles to spare (the space probe passing 500 km above the Earth), on August 18, 1999. Had there been any malfunction that caused the *Cassini* space probe to collide with the Earth, NASA's complete environmental impact study estimated that, in the worst case (with an acute angle of entry

in which *Cassini* would gradually burn up), a significant fraction of the 32.7 kg of plutonium-238 inside the RTGs would have been dispersed into the Earth's atmosphere so that up to five billion people could have been exposed, causing an estimated 500,000 cancer deaths, but the odds against that happening were nearly ten million to one.

## *Huygens* probe

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

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

# Important events and discoveries

## Venus and Earth fly-bys and the cruise to Jupiter

Picture of the Moon during flyby

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

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

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

## Jupiter flyby

Jupiter flyby picture

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

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

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

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

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

## Tests of Einstein's Theory of General Relativity

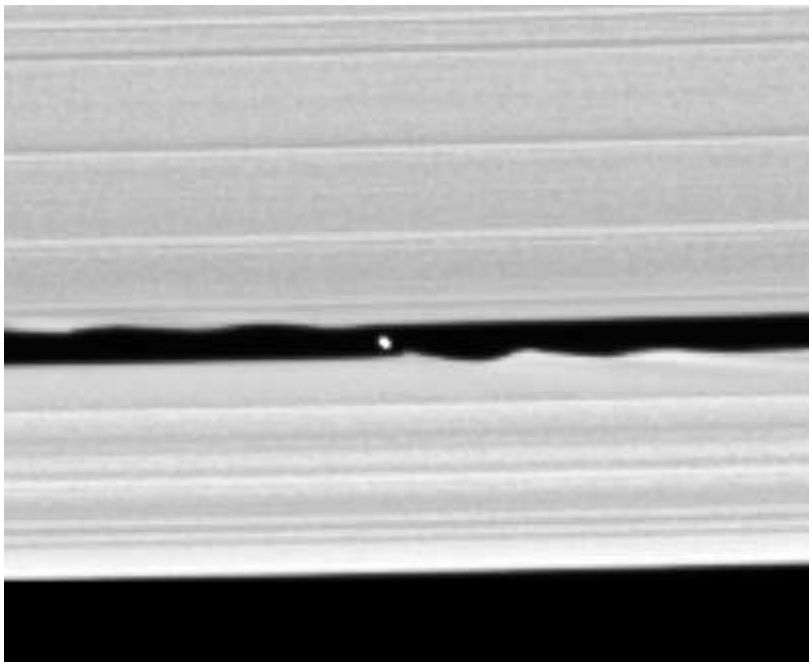
On October 10, 2003, the *Cassini* science team announced the results of tests of Einstein's Theory of General Relativity, which were done by using radio waves that were transmitted from the *Cassini* space probe.

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

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

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

## New moons of Saturn



Discovery photograph of moon Daphnis

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

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

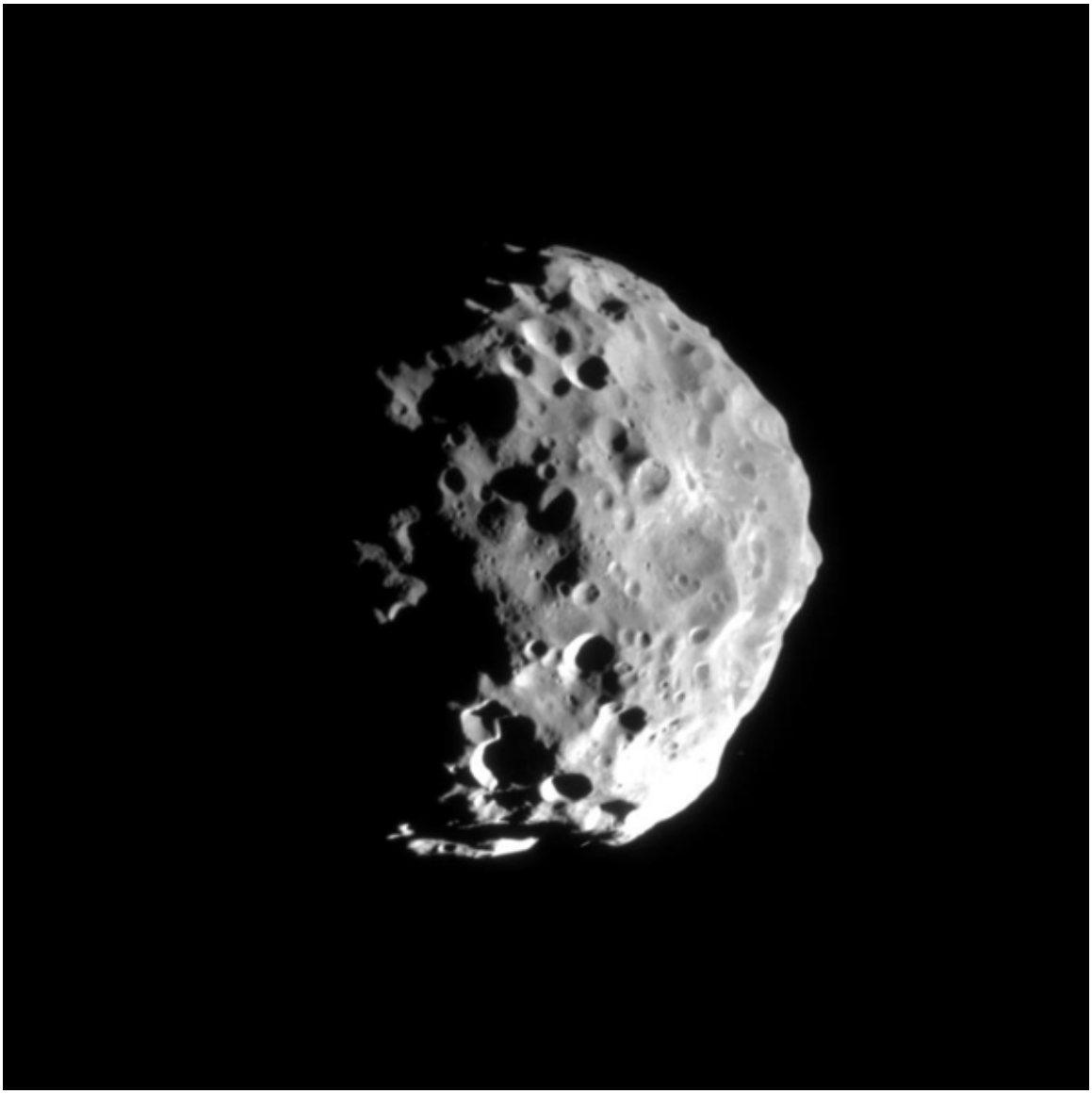


Image of Phoebe

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

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

## Phoebe flyby

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

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

## Saturn rotation

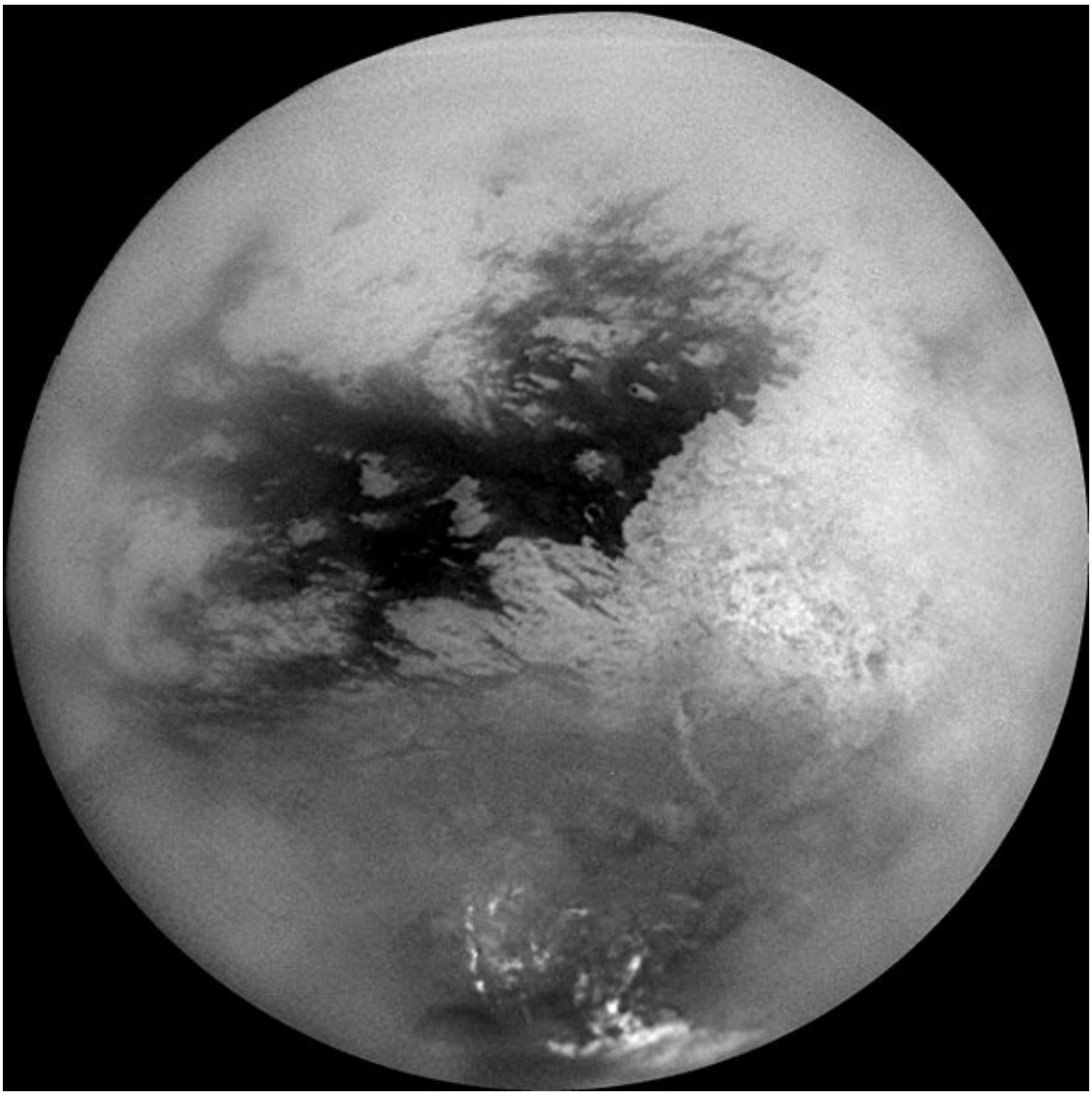
In an announcement on June 28, 2004, *Cassini* program scientists described the measurement of the rotational period of Saturn. Since there are no fixed features on the surface that can be used to obtain this period, the repetition of radio emissions was used. These new data agree with the latest values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

## Orbiting Saturn

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

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

## Titan flybys

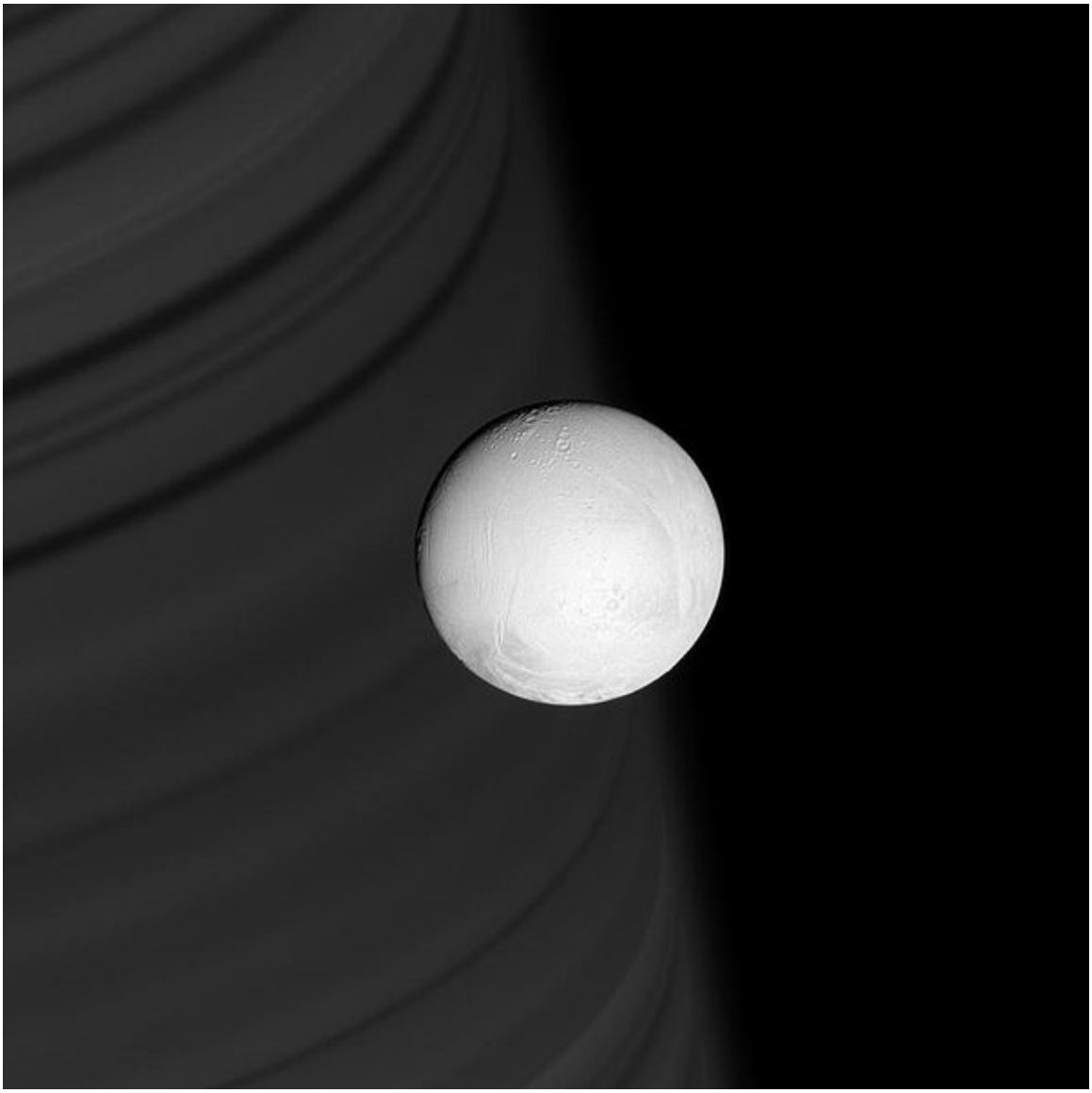


Titan's surface

*Cassini* had its first distant flyby of Saturn's largest moon, Titan, on July 2, 2004, only a day after orbit insertion, when it approached to within 339,000 km (211,000 mi) of Titan and provided the best look at the moon's surface to date. Images taken through special filters showed south polar clouds thought to be composed of methane and surface features with widely differing brightness. On October 27, 2004, the spacecraft executed the first of the 45 planned close flybys of Titan when it flew a mere 1,200 kilometers above the moon. Almost four gigabits of data were collected and transmitted to Earth, including the first radar images of the moon's haze-enshrouded surface. It revealed the surface of Titan (at least the area covered by radar) to be relatively level, with topography reaching no more than about 50 meters in altitude. The flyby provided a remarkable increase in imaging resolution over previous coverage. Images with up to 100 times

better "resolution" were taken and are typical of resolutions planned for subsequent Titan flybys. (Note that "resolution" refers to the clarity and precision of pictures, and that it has nothing to do with the overall size of the pictures in square centimeters, as is very commonly erroneously stated.)

### *Huygens'* encounter with Titan



Enceladus backdropped by Saturn's ring shadows

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

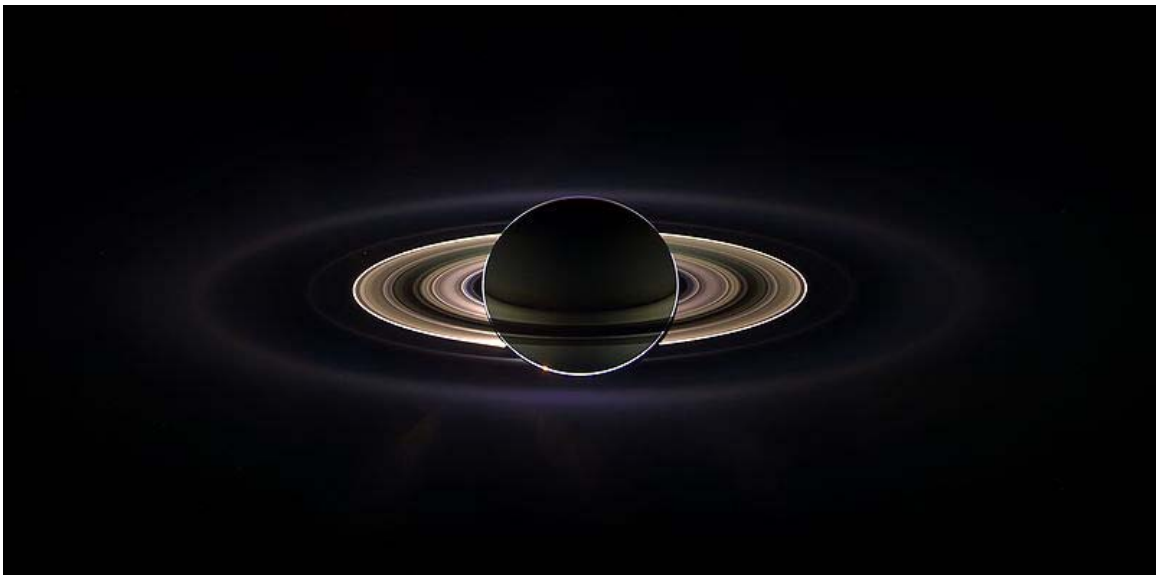
## Enceladus flybys

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

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

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

## Radio occultations of Saturn's rings



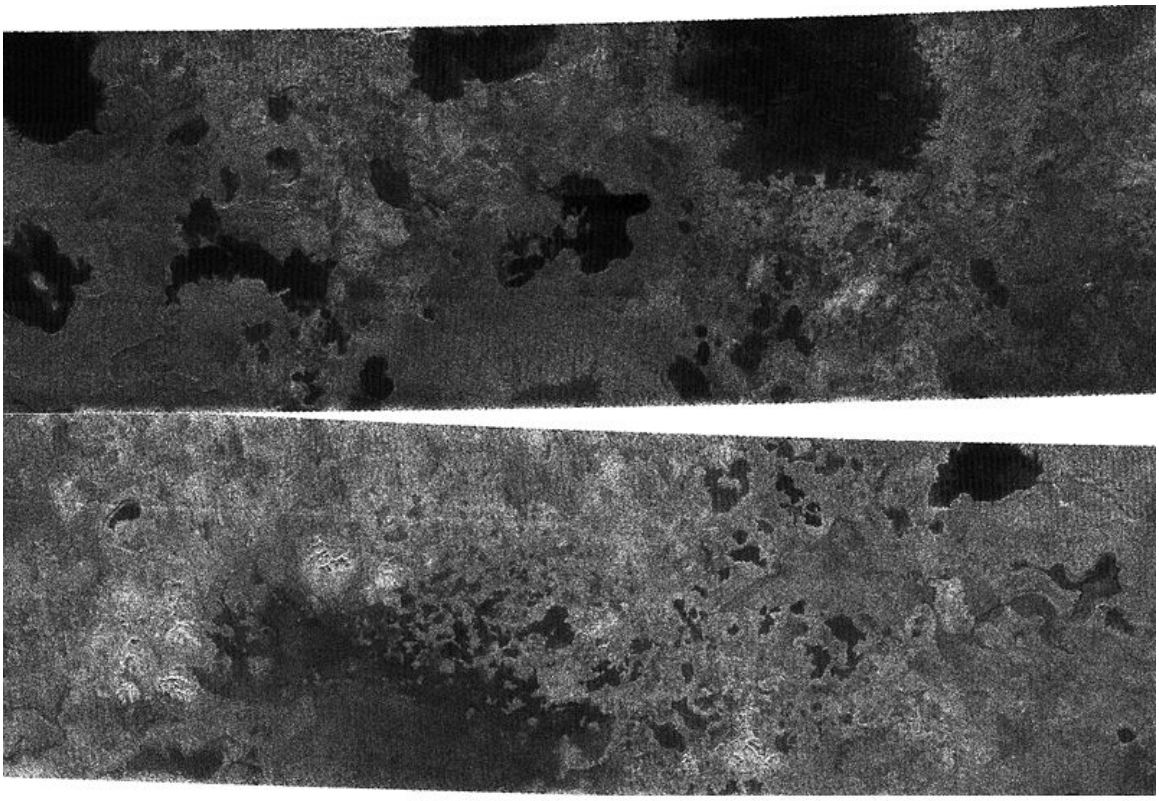
An eclipse of Saturn with the rings visible, taken in 2006

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

## Spoke phenomenon verified

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

## Lakes of Titan



Lakes of Titan

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

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

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

## Saturn hurricane

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

## Iapetus flyby

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

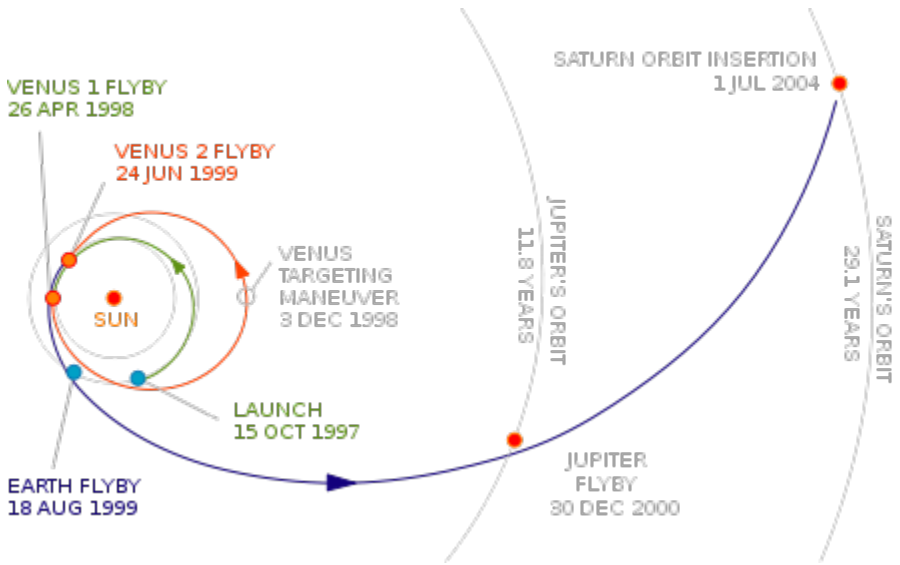
## Mission extension

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

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

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

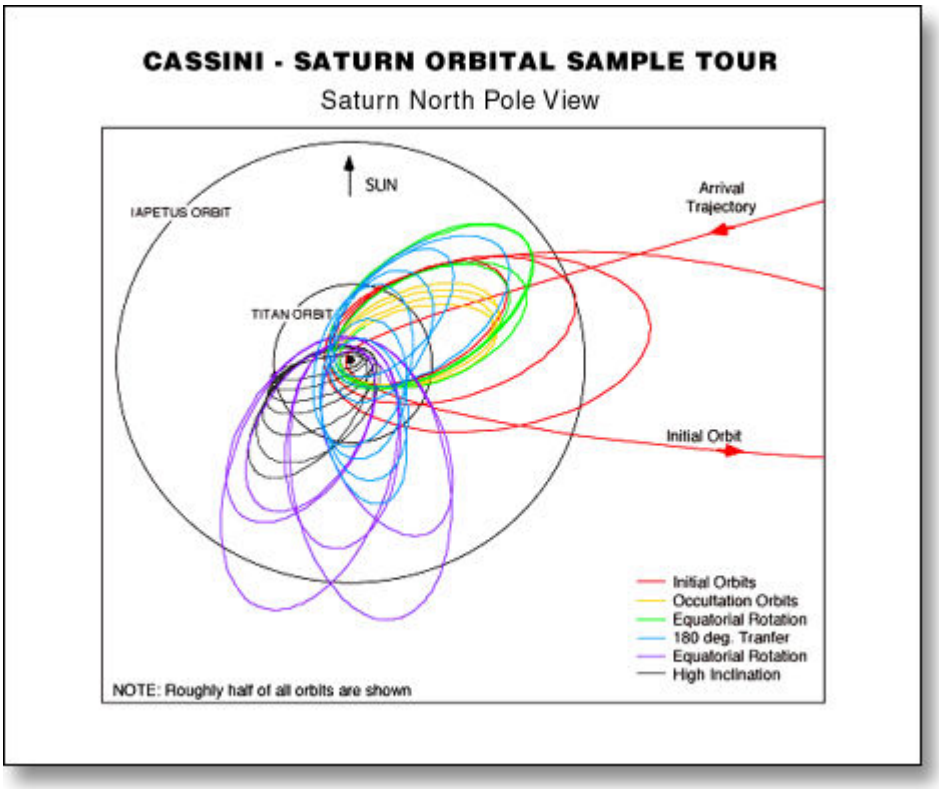
# Trajectory



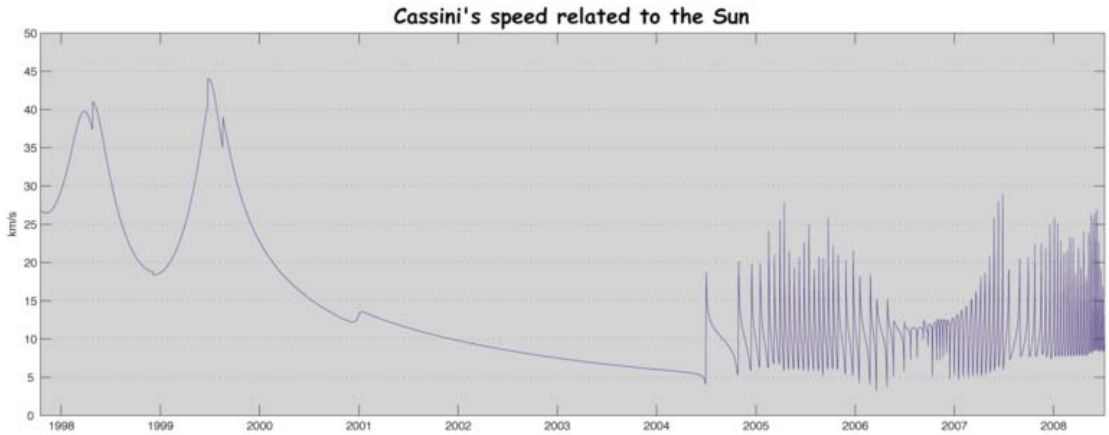

The initial gravitational-assist trajectory of *Cassini–Huygens*

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

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




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




The *Cassini* craft's speed relative to the Sun. The various gravitational slingshots form visible peaks on the left, while the periodic variation on the right is caused by the spacecraft's orbit around Saturn. The data came from the JPL Horizons Ephemeris System in 2005. The speed above is instantaneous velocity in kilometers per second. The date/time is UTC in Spacecraft Event Time, which is from 1997-Oct-16 00:00:01 to

2008-Jul-06 23:59:59 UTC, with two leap seconds during this period. Note also that the minimum velocity achieved during its Saturnian orbit is more or less equal to Saturn's own orbital velocity, which is the ~5.0 km/sec. velocity which the *Cassini* craft matched to enter orbit!

# Chapter 8

# 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<br>(33 years, 6 months, and 4 days ago) |
| **Launch vehicle** | Titan IIIE / Centaur |
| **Launch site** | Space Launch Complex 41<br>Cape Canaveral Air Force Station |
| **Mission duration** | In Progress (Interstellar mission) |

| | |
|---|---|
| | (31 years, 7 months, and 15 days elapsed)<br>Jupiter flyby<br>*(completed 1979-08-05)*<br>Saturn flyby<br>*(completed 1981-09-25)*<br>Uranus flyby<br>*(completed 1986-02-25)*<br>Neptune flyby<br>*(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, 6 months, and 4 days as of today's date (24 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

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.

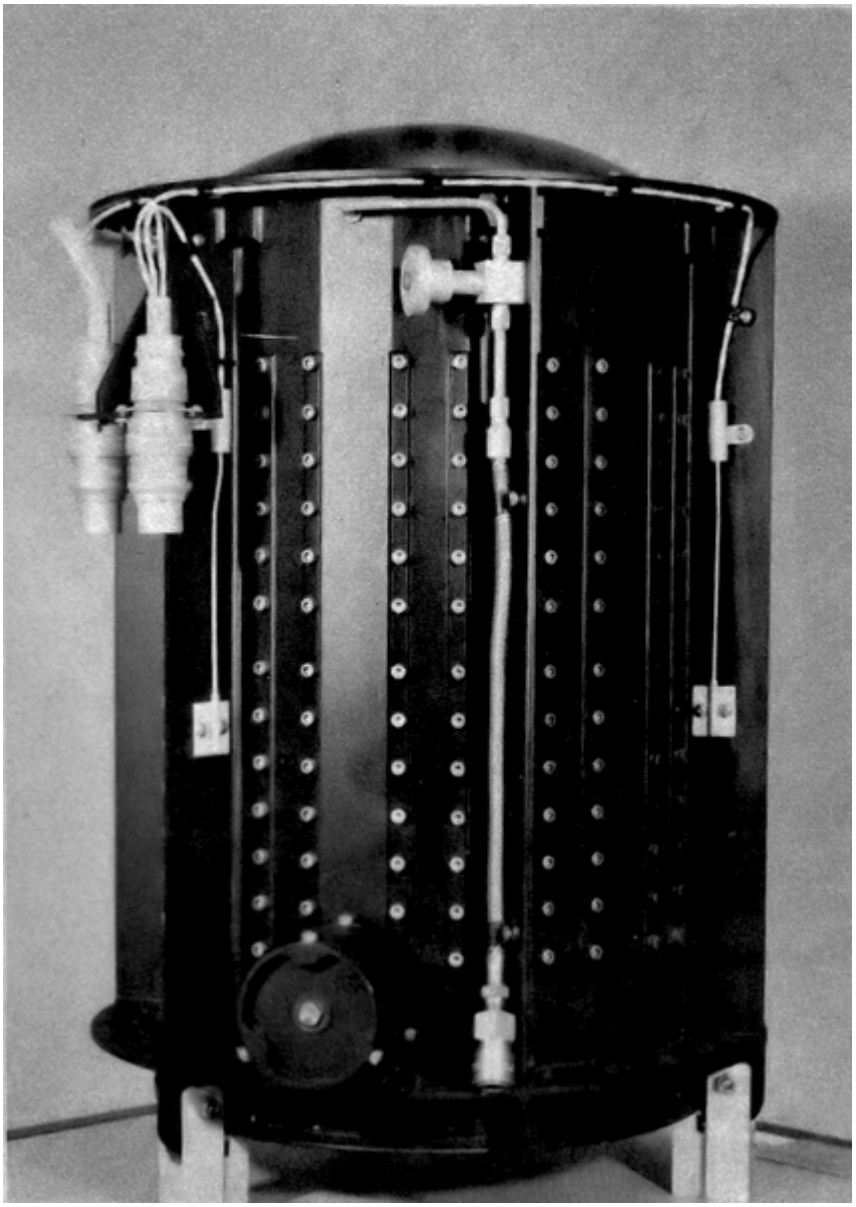
## Spacecraft design

Constructed by the Jet Propulsion Laboratory, *Voyager 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

Built with the intent for eventual interstellar travel, *Voyager 2* 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. |

**Filters**

| Narrow Angle Camera Filters | | | | Wide Angle Camera Filters | | | |
|---|---|---|---|---|---|---|---|
| **Name** | **Wavelength** | **Spectrum** | **Sensitivity** | **Name** | **Wavelength** | **Spectrum** | **Sensitivity** |
| Clear | 280nm - 640nm | | | Clear | 280nm - 640nm | | |
| UV | 280nm - 370nm | | | ' | ' | | ' |
| Violet | 350nm - 450nm | | | Violet | 350nm - 450nm | | |
| Blue | 430nm - 530nm | | | Blue | 430nm - 530nm | | |
| ' | ' | | ' | $CH_4$-U | 536nm - 546nm | | |
| Green | 530nm - 640nm | | | Green | 530nm - 640nm | | |
| ' | ' | | ' | Na-D | 588nm - 590nm | | |
| Orange | 590nm - 640nm | | | 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 | (**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. |

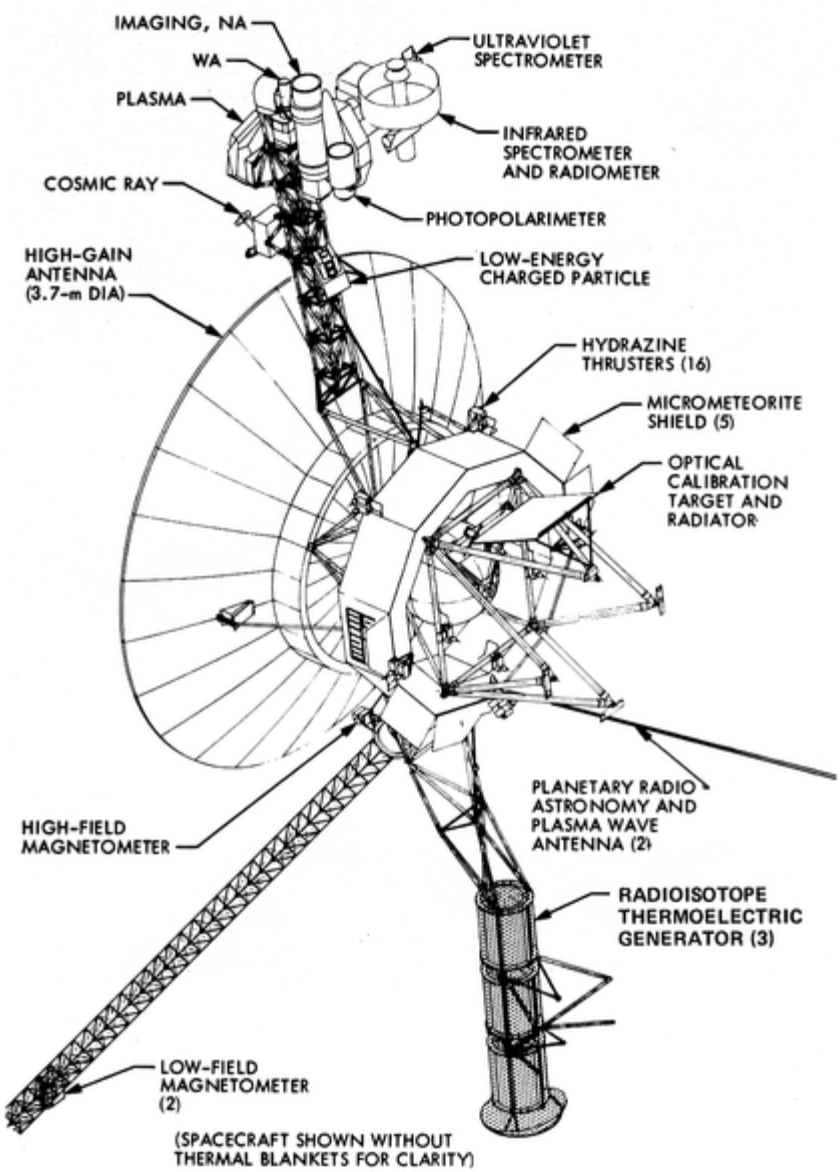
- **Principal investigator:** Rudolf Hanel / NASA Goddard Space Flight Center (PDS/PRN website)
- **Data:** PDS/PRN data catalog, PDS/PRN expanded data catalog **(**VGIRIS_0001, VGIRIS_002**)**

| | | |
|---|---|---|
| Ultraviolet Spectrometer (**disabled**) | (**UVS**) | Designed to measure atmospheric properties, and to measure radiation. |

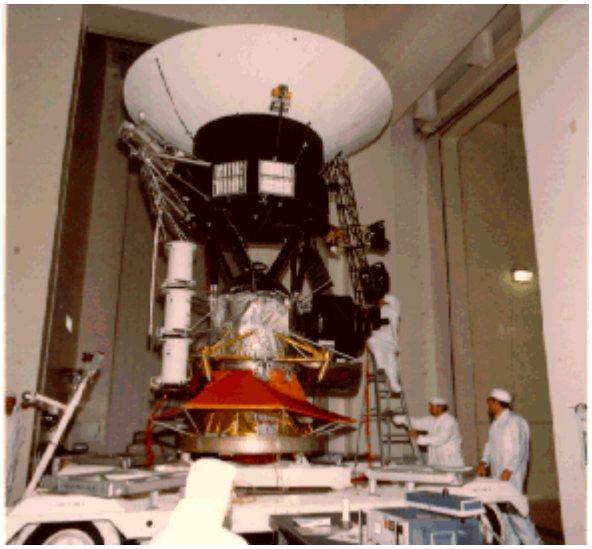
- **Principal investigator:** A. Broadfoot / University of Southern California (PDS/PRN website)

| | | |
|---|---|---|
| | | • **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.<br>• **Principal investigator:** Norman Ness / NASA Goddard Space Flight Center (website)<br>• **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.<br>• **Principal investigator:** John Richardson / MIT (website)<br>• **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.<br>• **Principal investigator:** Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website)<br>• **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.<br>• **Principal investigator:** Edward Stone / CalTech / NASA Goddard Space Flight Center (website)<br>• **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.<br>• **Principal investigator:** James Warwick / University of Colorado<br>• **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.<br>• **Principal investigator:** Arthur Lane / JPL (PDS/PRN website)<br>• **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.<br>• **Principal investigator:** Donald Gurnett / University of Iowa (website)<br>• **Data:** PDS/PPI data catalog, NSSDC data archive |

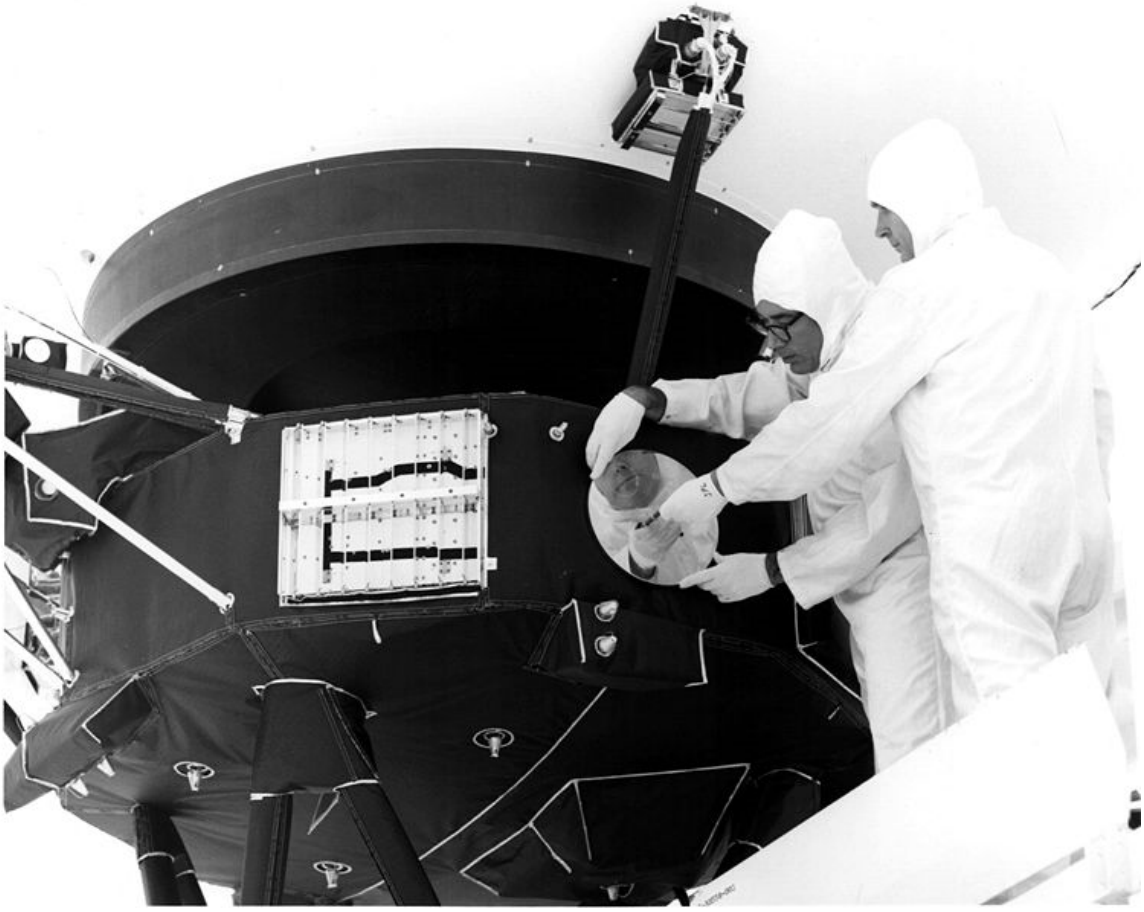
## Images of the spacecraft




*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

# Mission profile

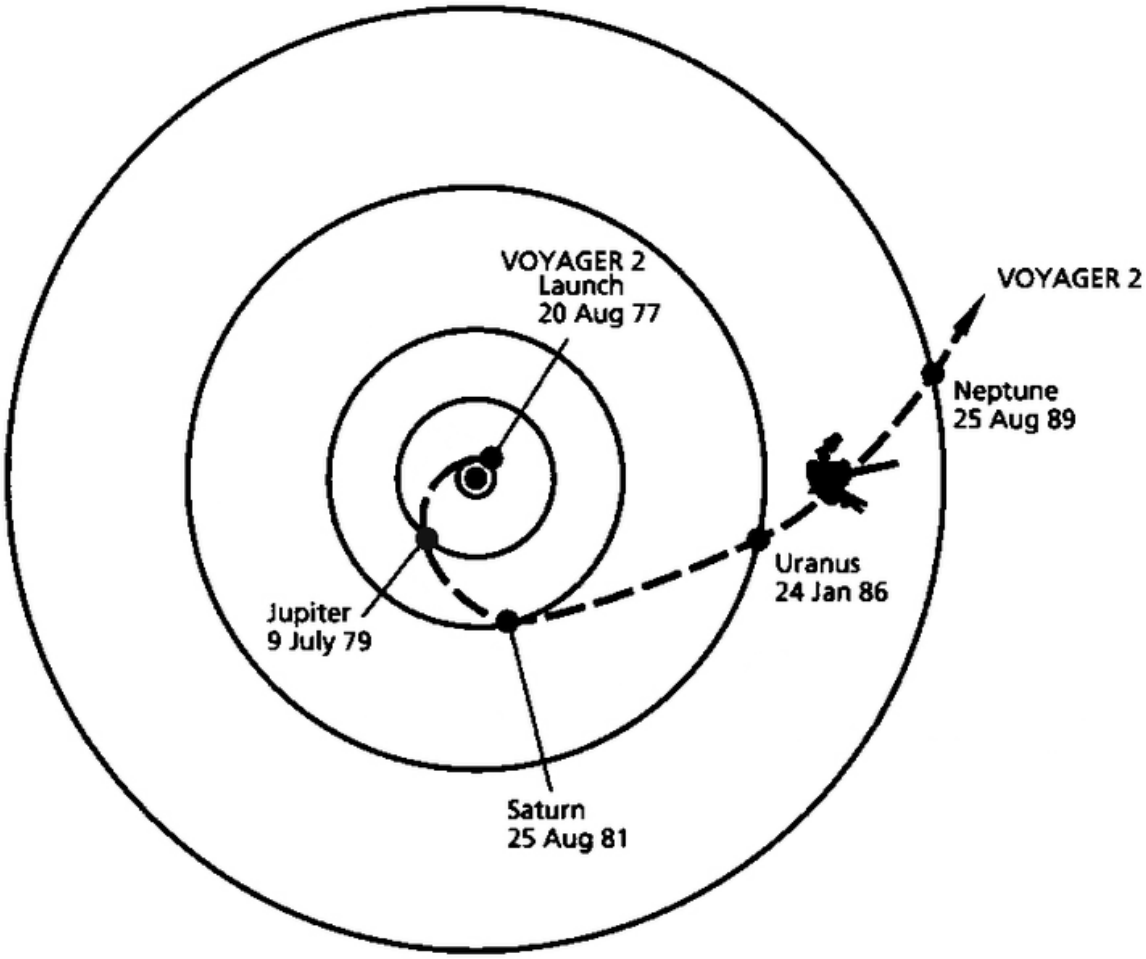
**Timeline of travel**

| 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*. (***see diagram***) |
| 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<br>**Time** **Event** |
| 1981-06-05 | Start Saturn observation phase.<br>**Time** **Event** |
| 1985-11-04 | Start Uranus observation phase.<br>**Time** **Event** |
| 1985-11-04 | Start Neptune observation phase.<br>**Time** **Event** |
| 1989-10-02 | Begin Voyager Interstellar Mission. |

## 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.

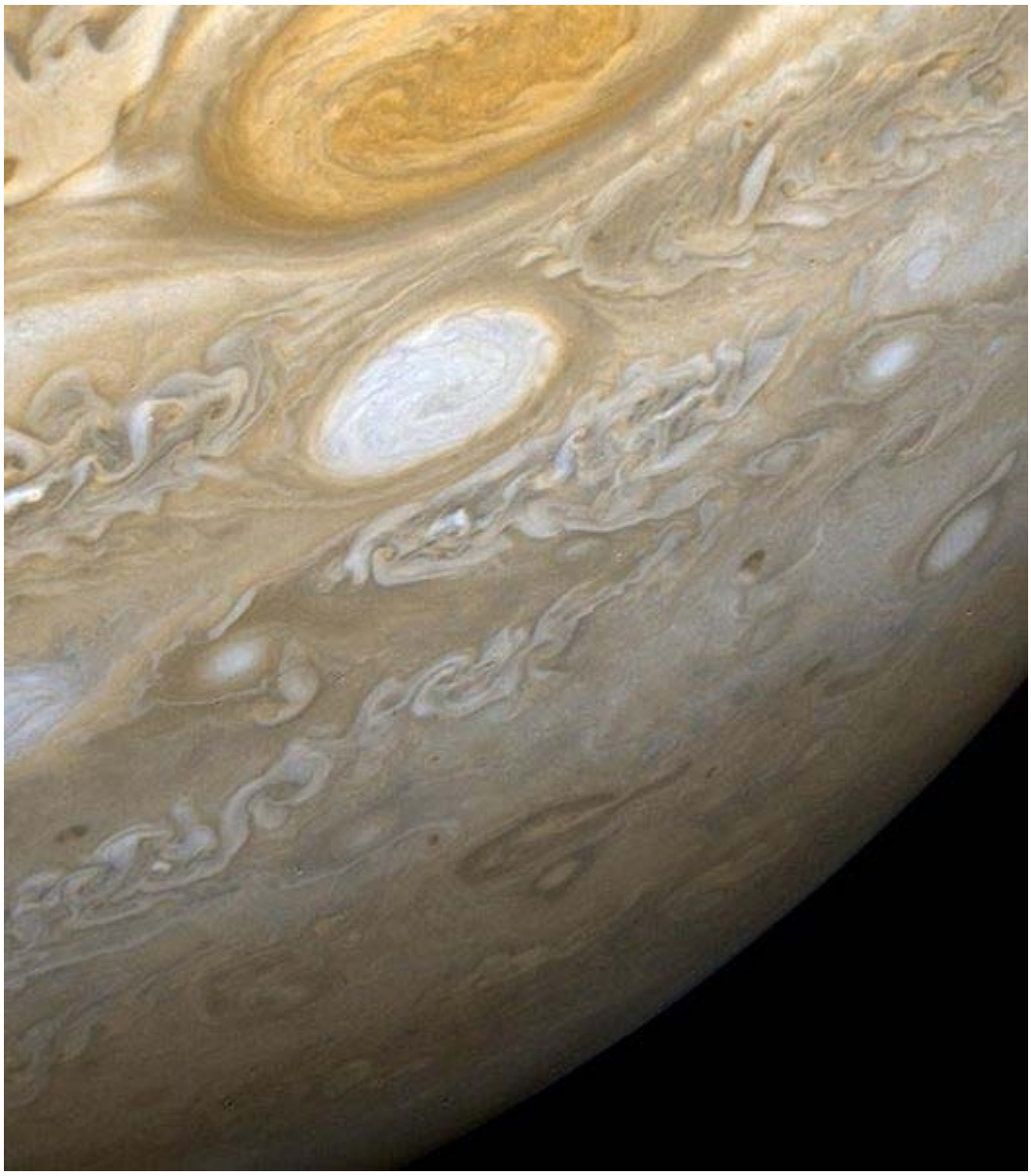
The Great Red Spot was revealed as a complex storm moving in a counterclockwise direction. An array of other smaller storms and eddies were found throughout the banded clouds.

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.

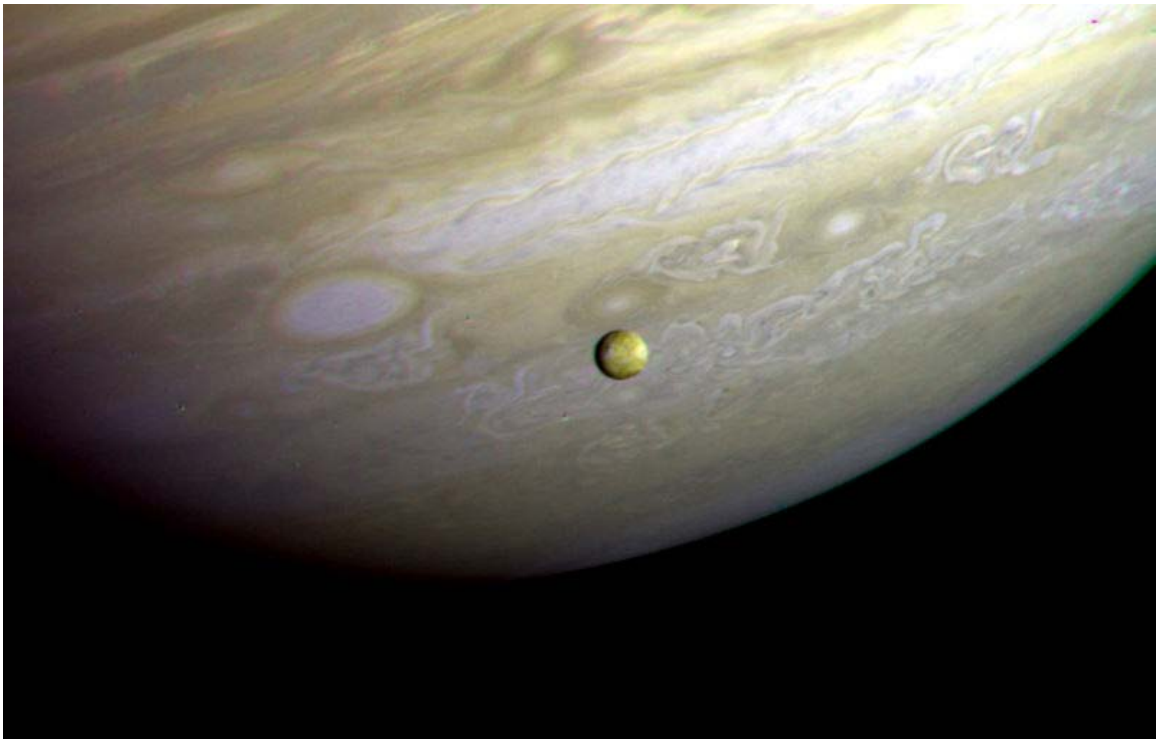
The moon Europa displayed a large number of intersecting linear features in the low-resolution photos from *Voyager 1*. At first, scientists believed the features might be deep

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.

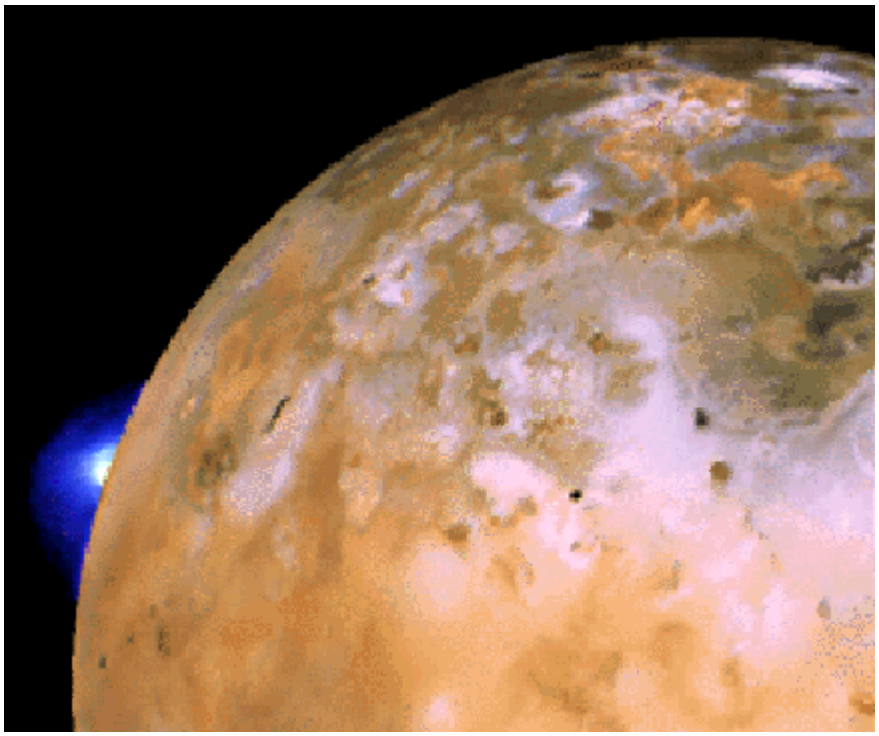
Two new, small satellites, Adrastea and Metis, were found orbiting just outside the ring. A third new satellite, Thebe, was discovered between the orbits of Amalthea and Io.



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



A transit of Io across Jupiter, July 9, 1979

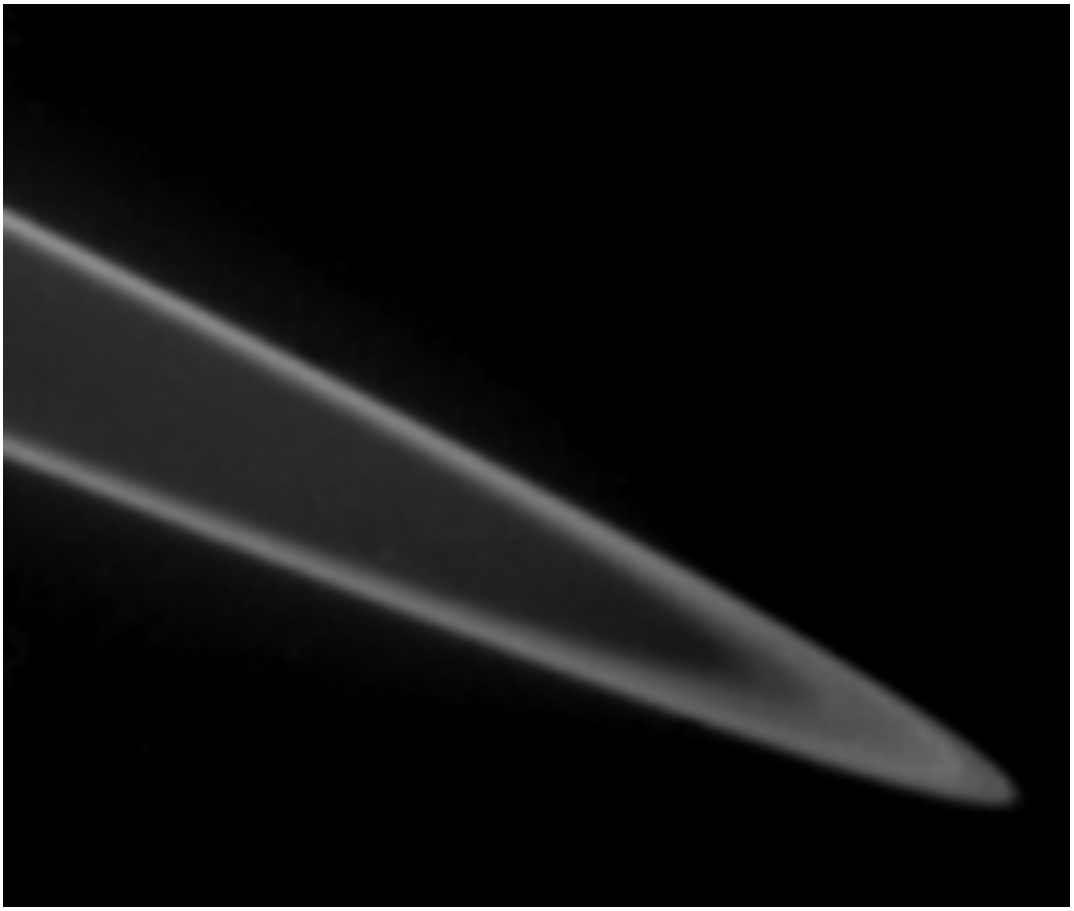


Eruption of a volcano on Io, photographed by Voyager 2

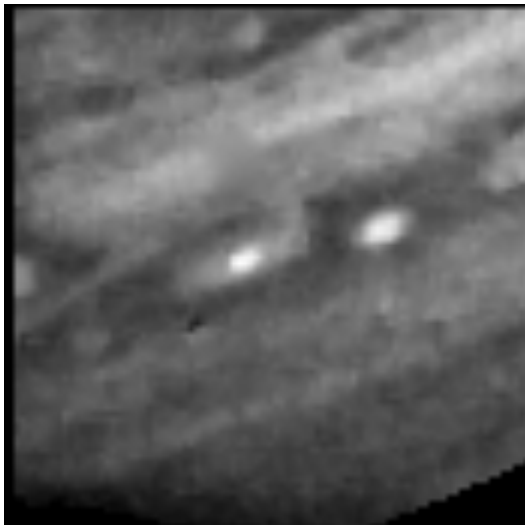
A color mosaic of Europa

A color mosaic of Ganymede

Callisto photographed at a distance of 1 million kilometers



One faint ring of Jupiter photographed during the flyby



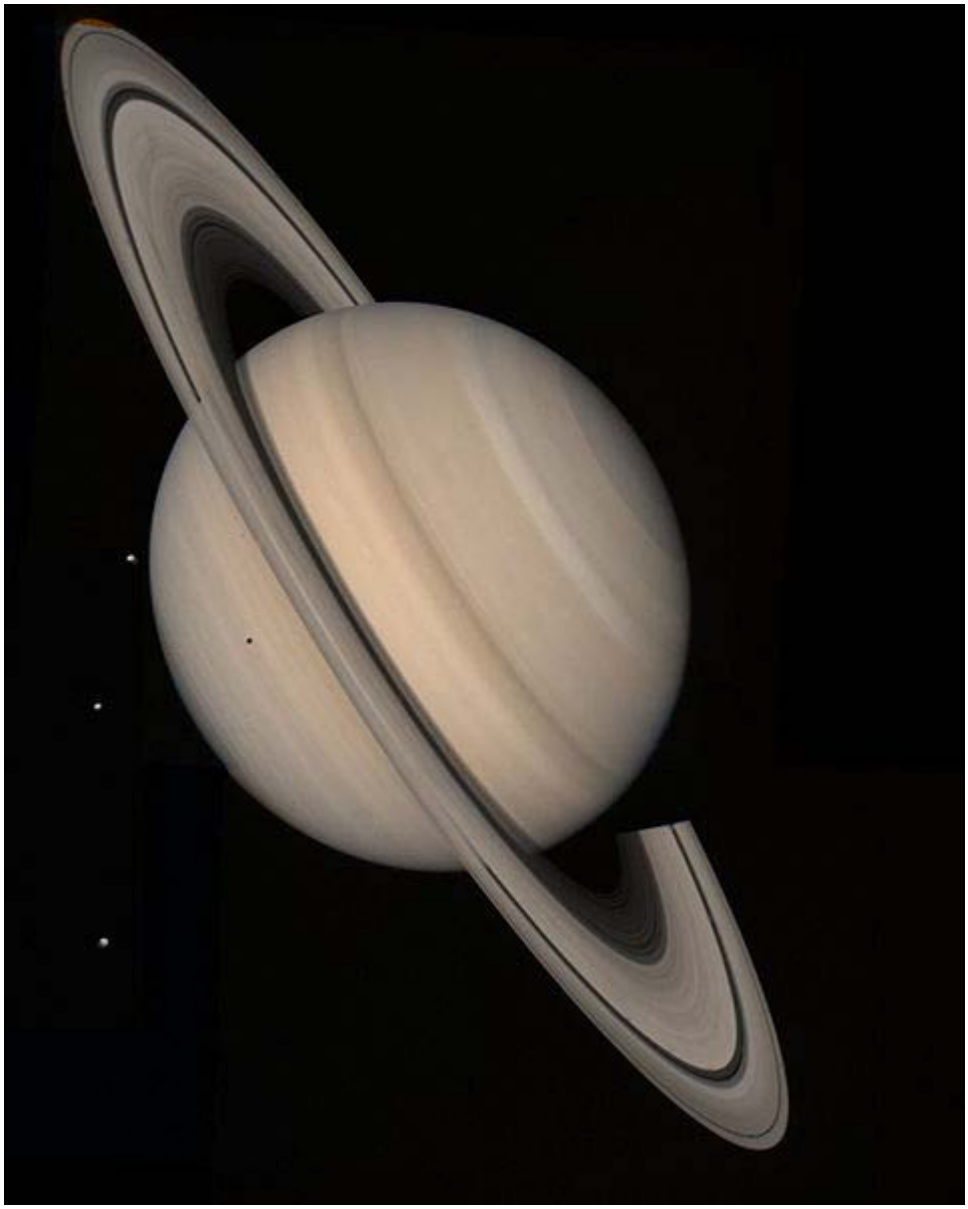
Atmospheric eruptive event on Jupiter

## Encounter with Saturn

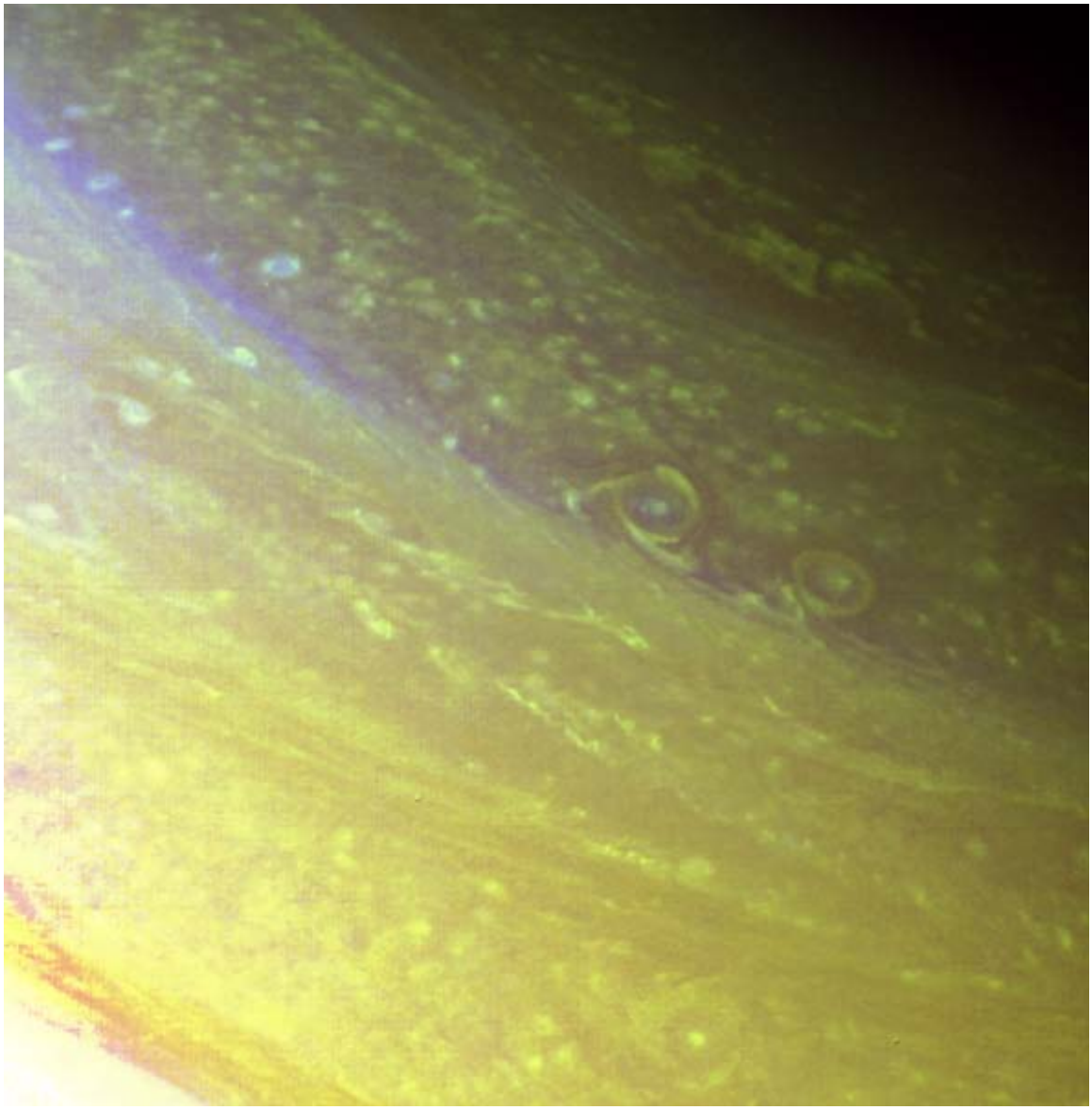
The closest approach to Saturn occurred on August 26, 1981.

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.

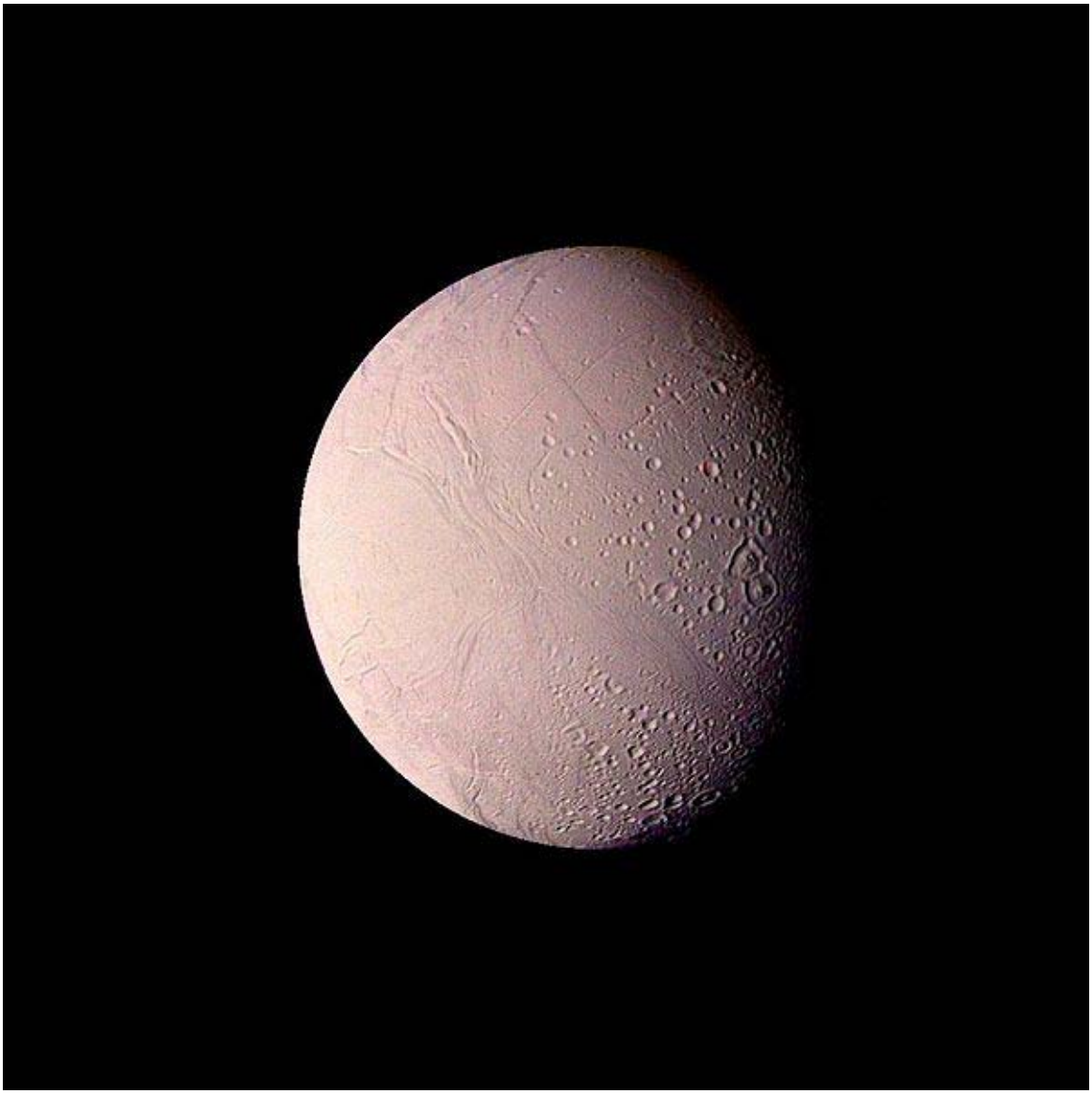
After the fly-by of Saturn, the camera platform of *Voyager 2* locked up briefly, putting plans to officially extend the mission to Uranus and Neptune in jeopardy. Fortunately, the mission's engineers were able to fix the problem (caused by an overuse that temporarily depleted its lubricant), and the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



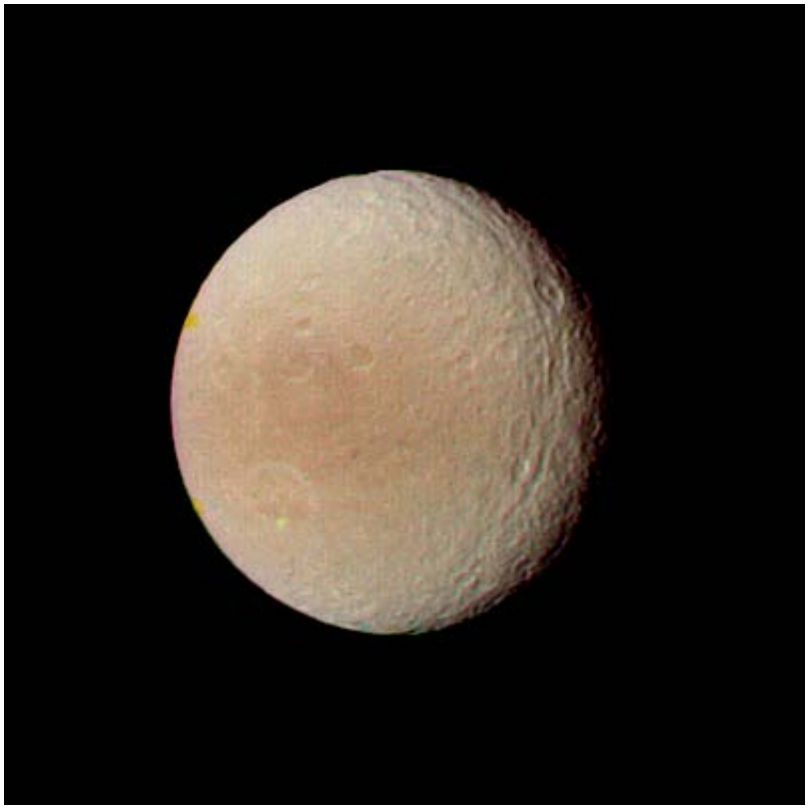
*Voyager 2* Saturn approach view



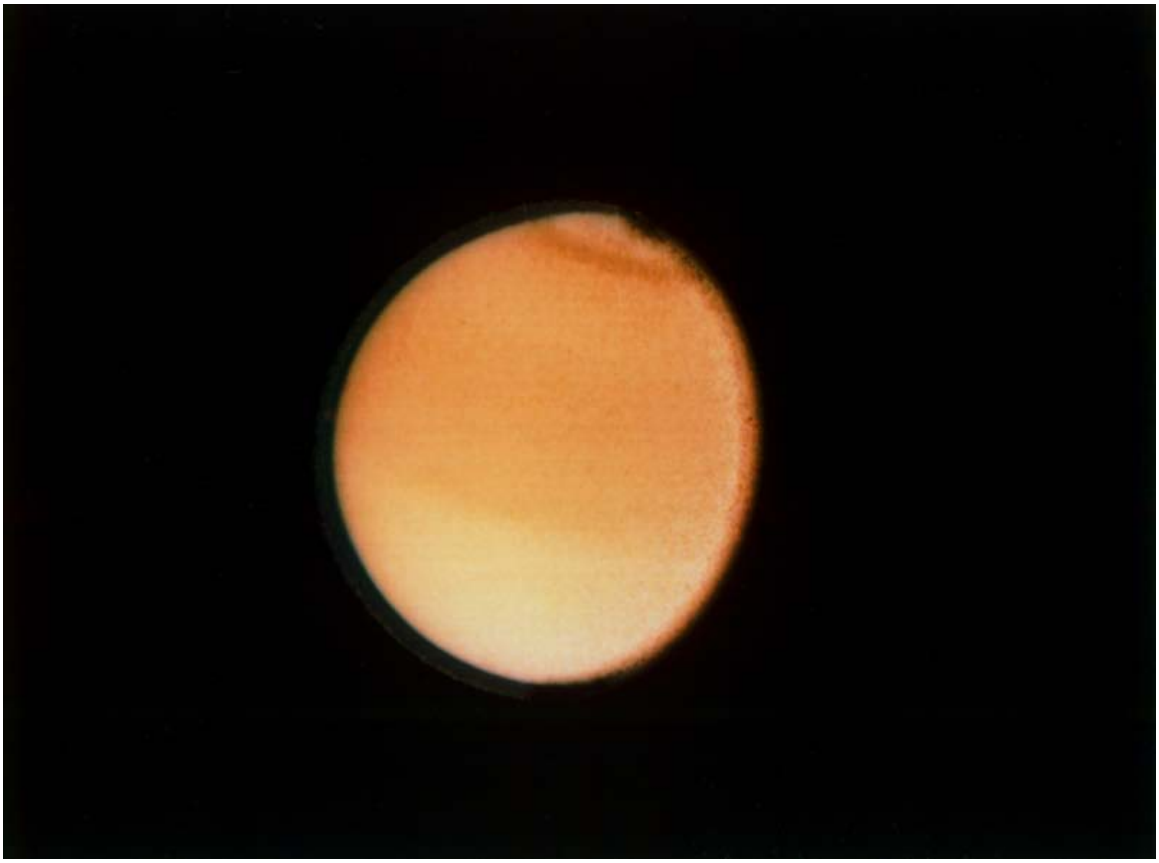
North, polar region of Saturn imaged in orange and UV filters



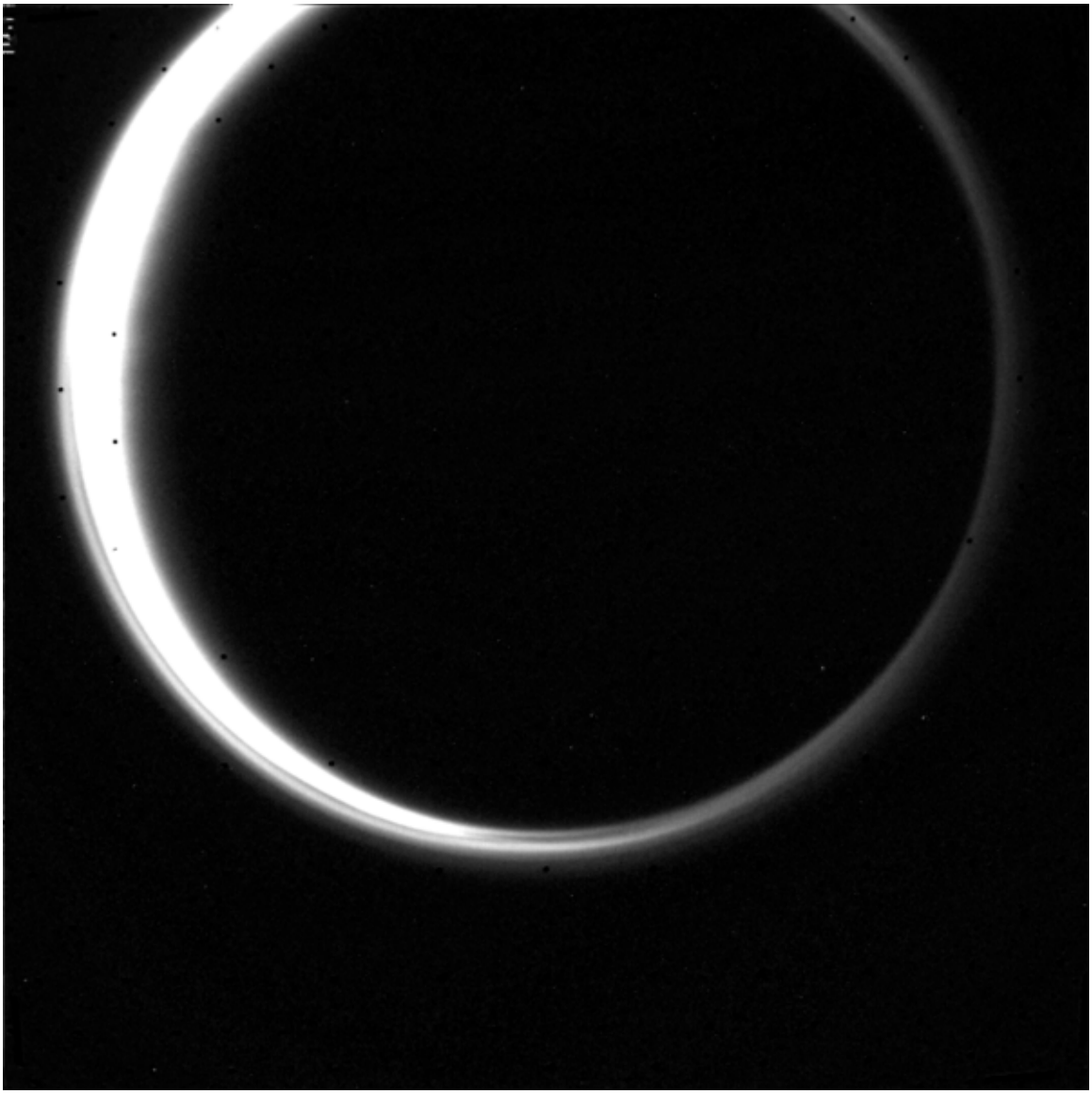
Color image of Enceladus showing terrain of widely varying ages



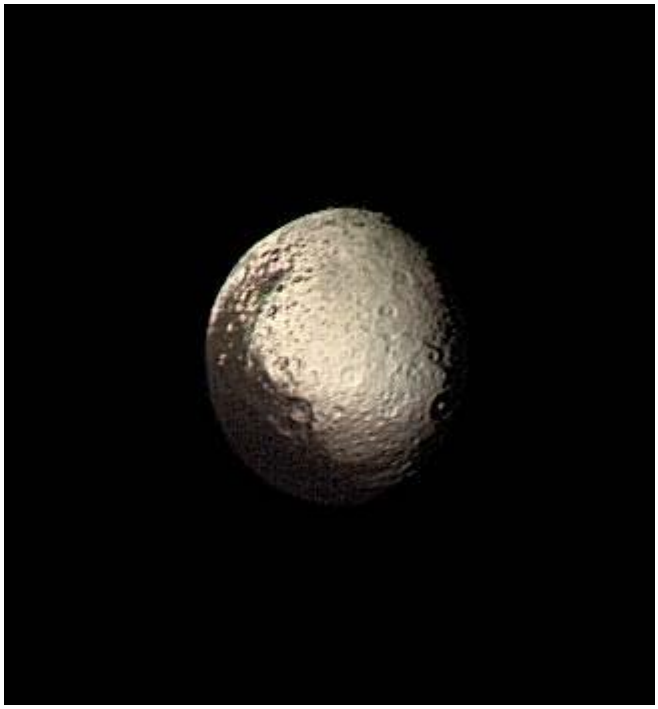
Cratered surface of Tethys at 594,000 km



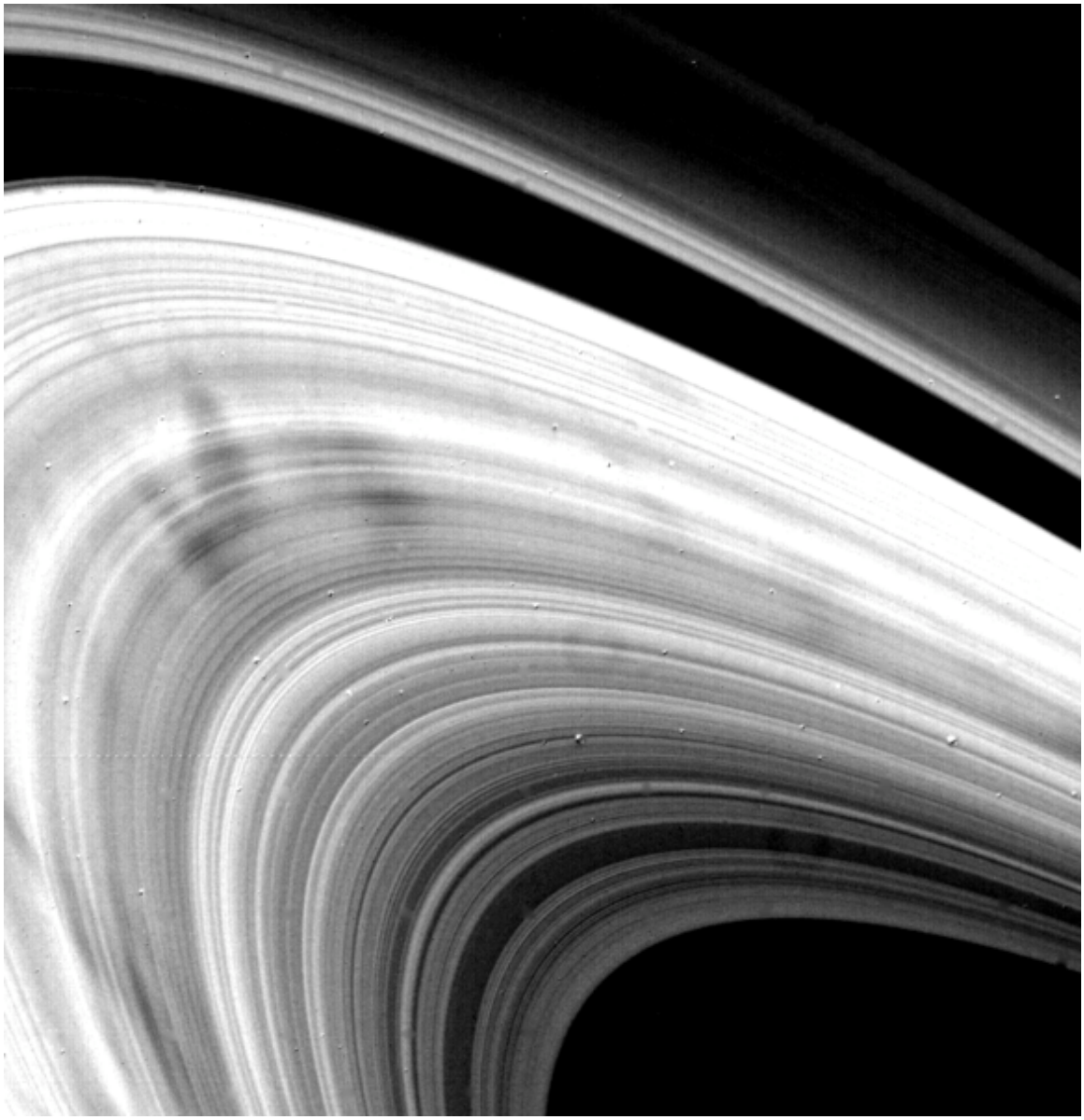
Atmosphere of Titan imaged from 2.3 million km



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.

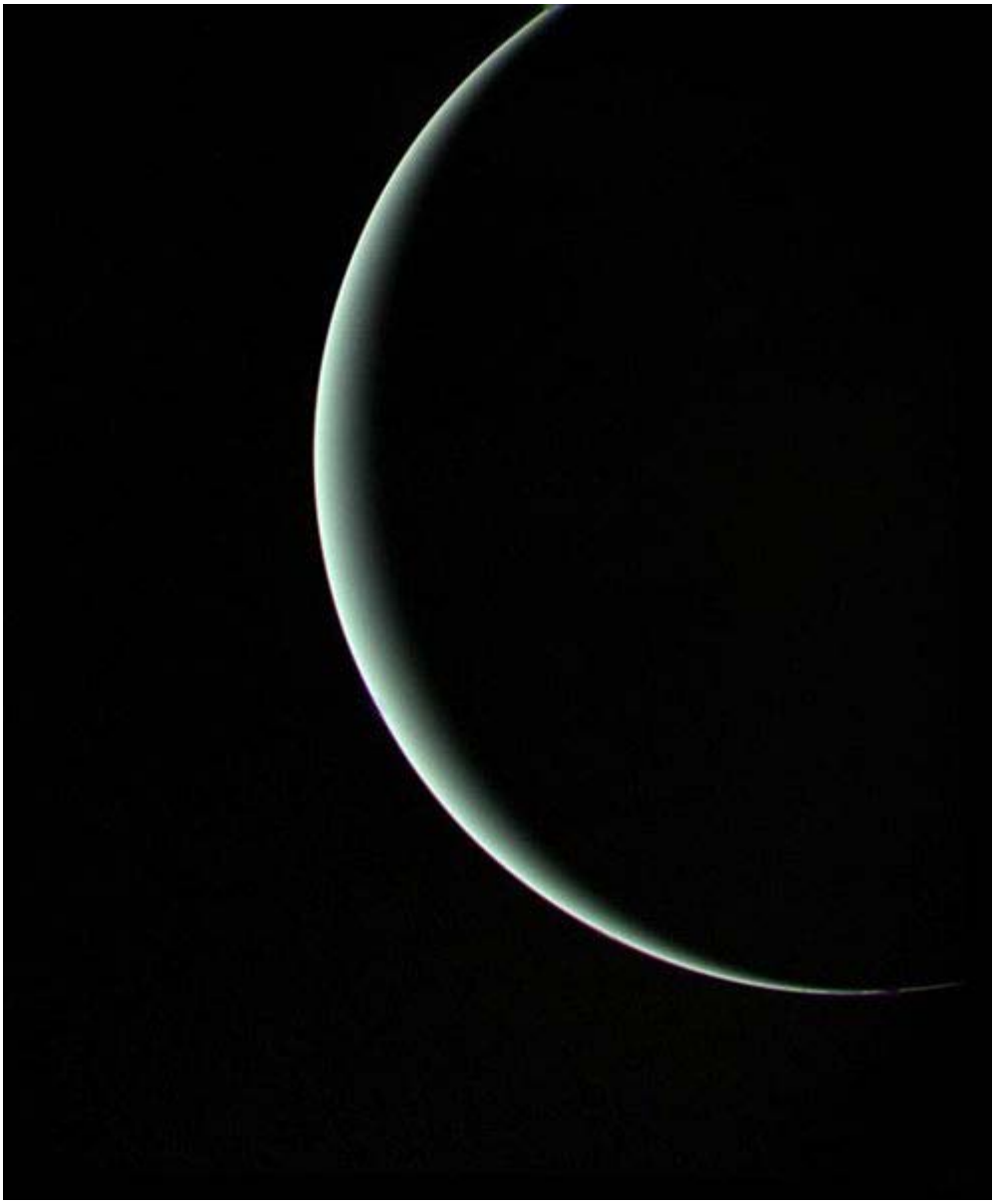
The radiation belts of Uranus were found to be of an intensity similar to those of Saturn. The intensity of radiation within the Uranian belts is such that irradiation would "quickly" darken—within 100,000 years—any methane that is trapped in the icy surfaces of the inner moons and ring particles. This 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.

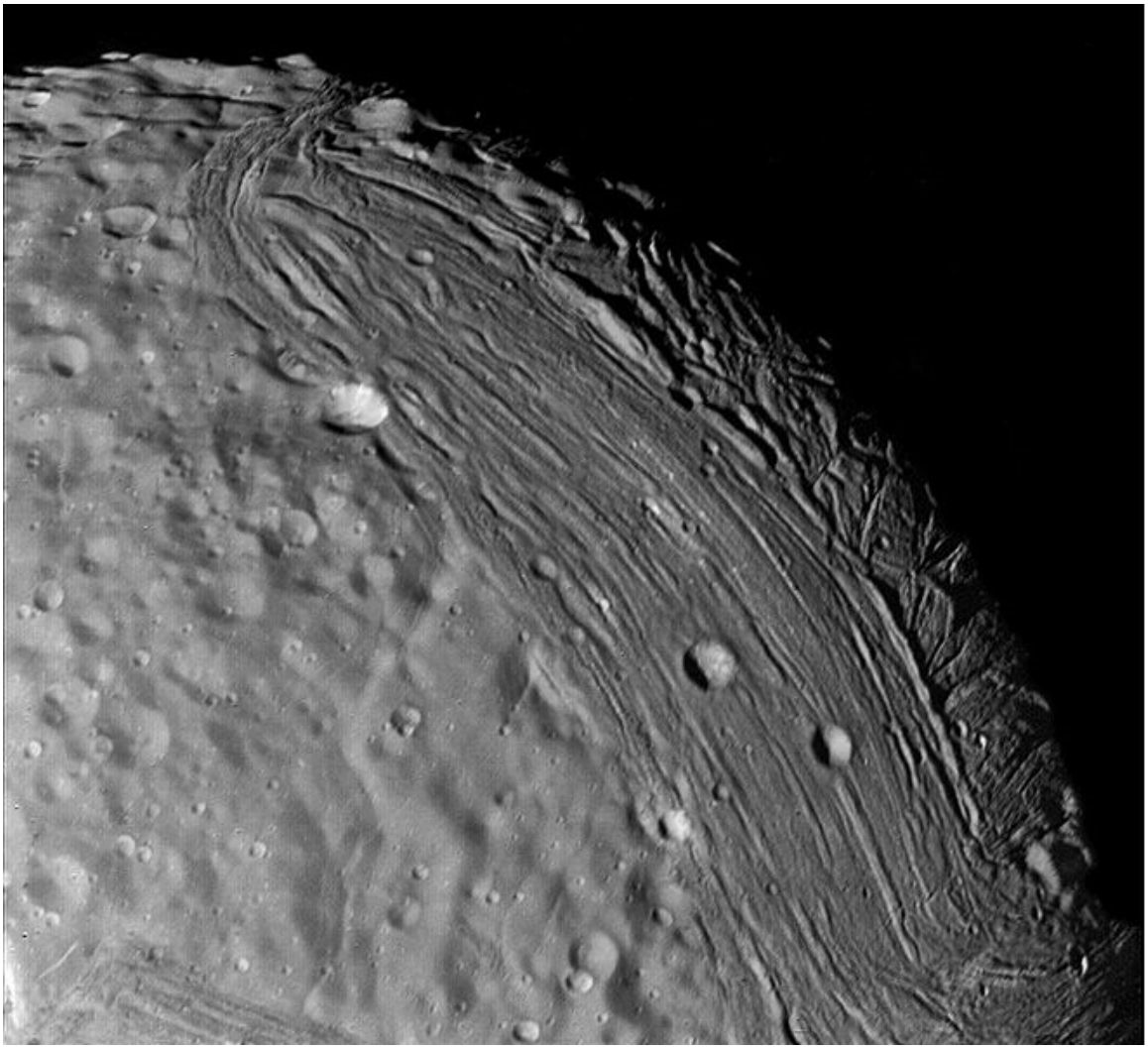
The Uranian moon Miranda, the innermost of the five large moons, was discovered to be one of the strangest bodies yet seen in the Solar System. Detailed images from *Voyager 2's* flyby of Miranda showed huge canyons made from geological faults as deep as 20 kilometers (12 miles), terraced layers, and 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.

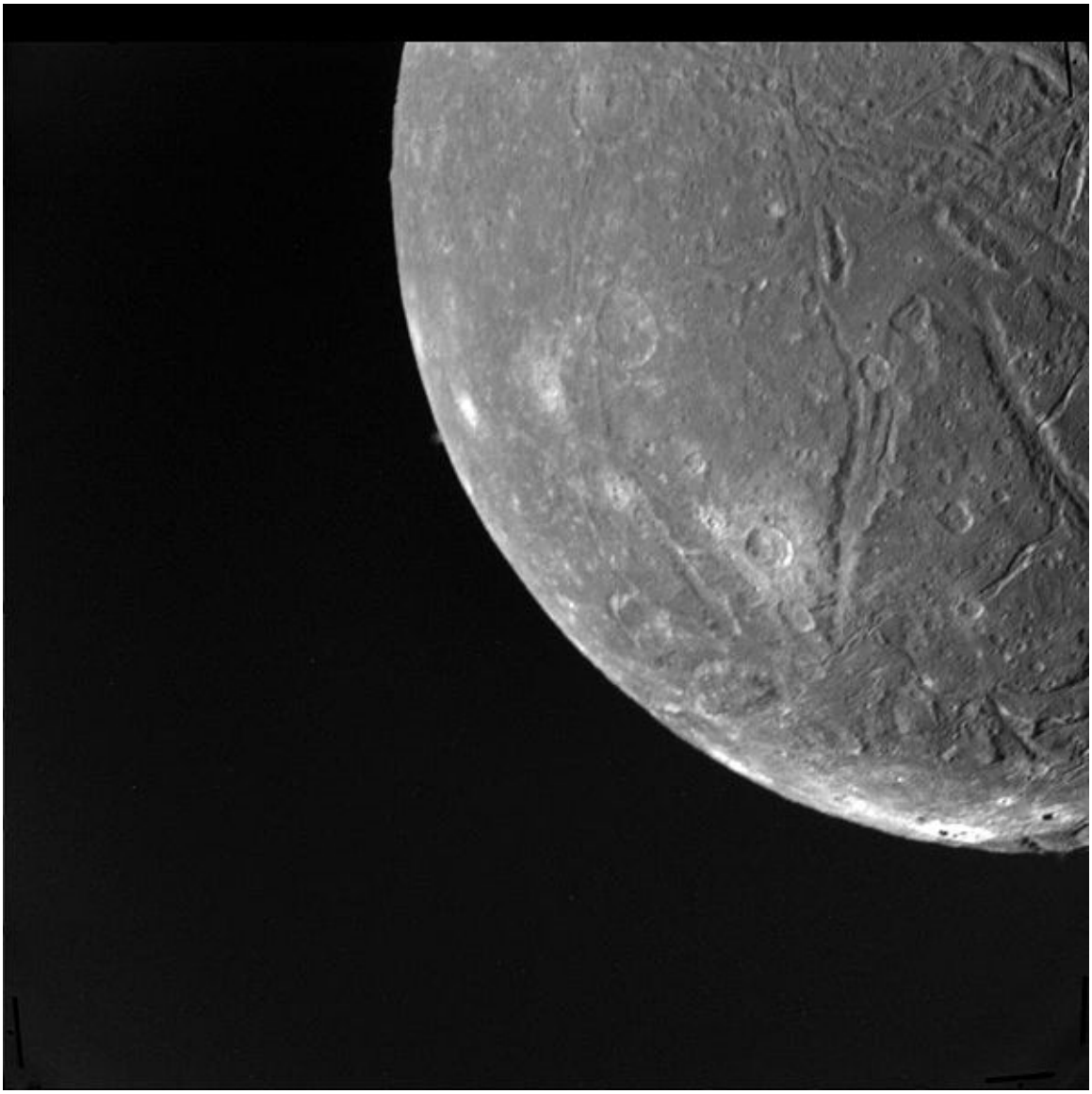
Uranus viewed from 18 million km.



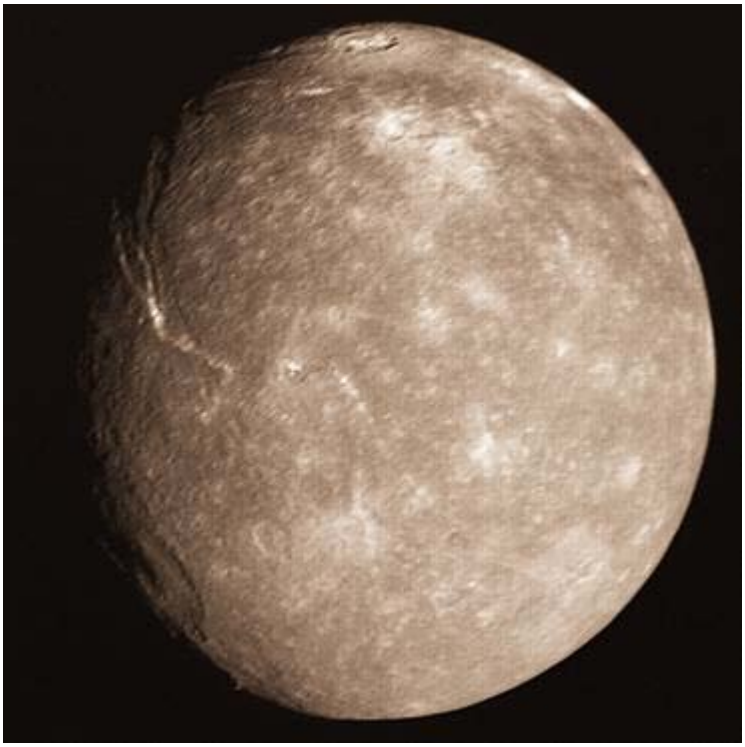
Departing image of crescent Uranus



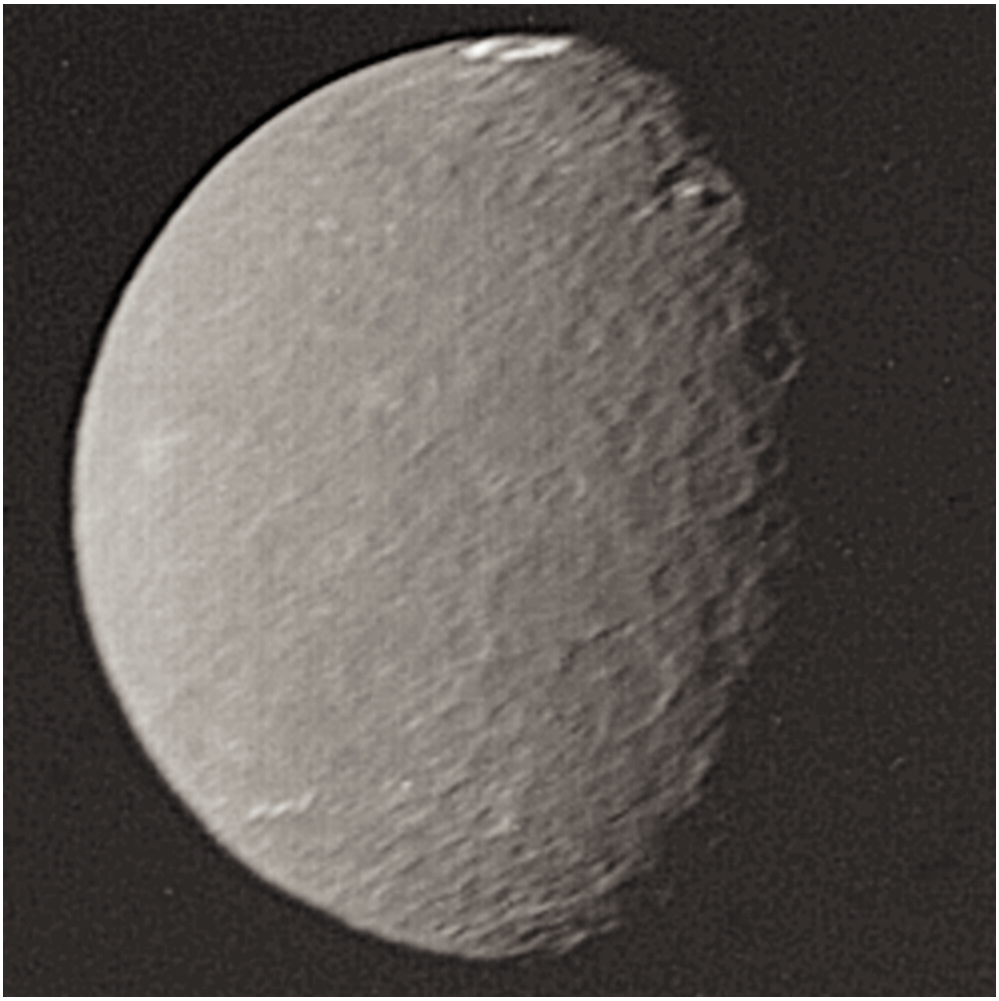
Fractured surface of Miranda



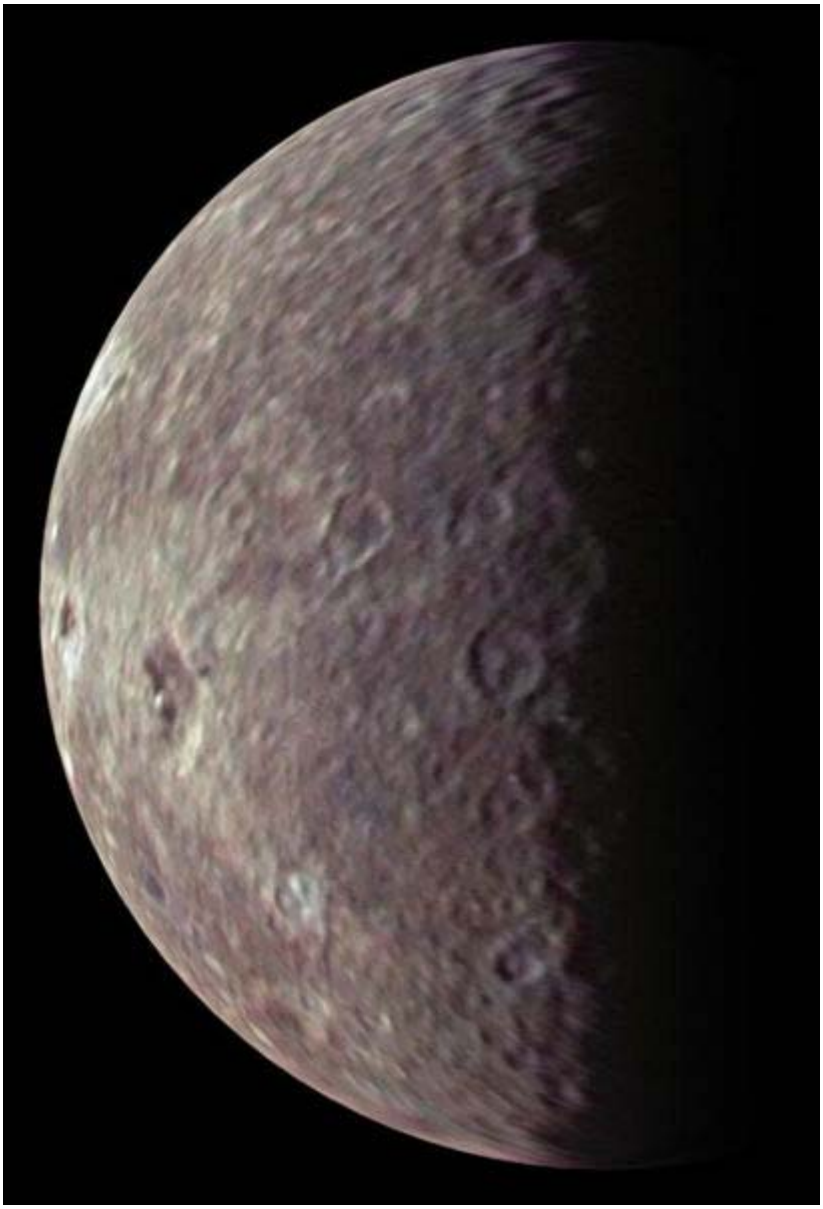
Ariel as imaged from 130,000 km.



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.

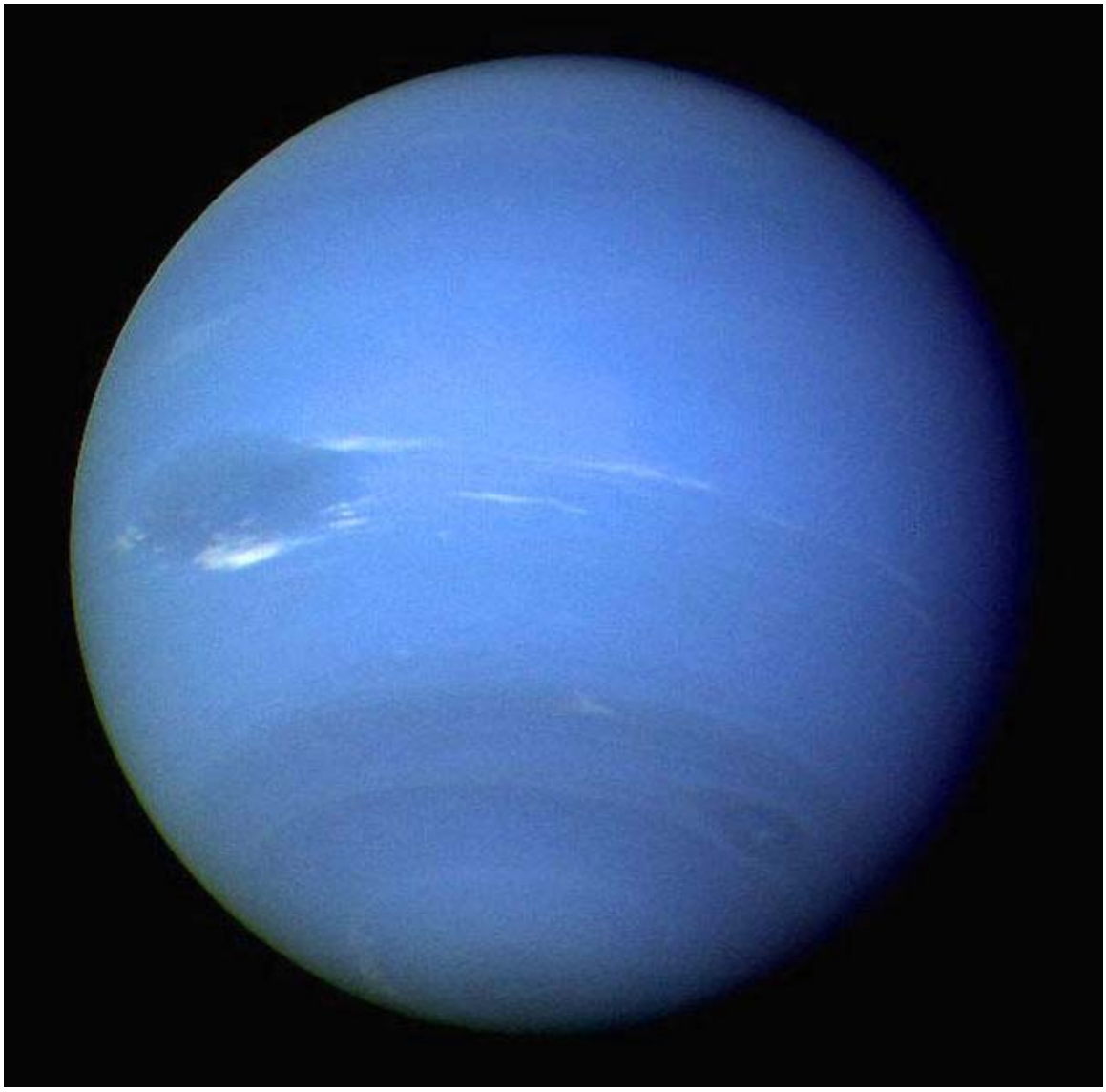
While in the neighborhood of Neptune, *Voyager 2* discovered the "Great Dark Spot", which has since disappeared, according to observations by the Hubble Space Telescope. Originally thought to be a large cloud itself, the "Great Dark Spot" was later hypothesized to be a hole in the visible cloud deck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

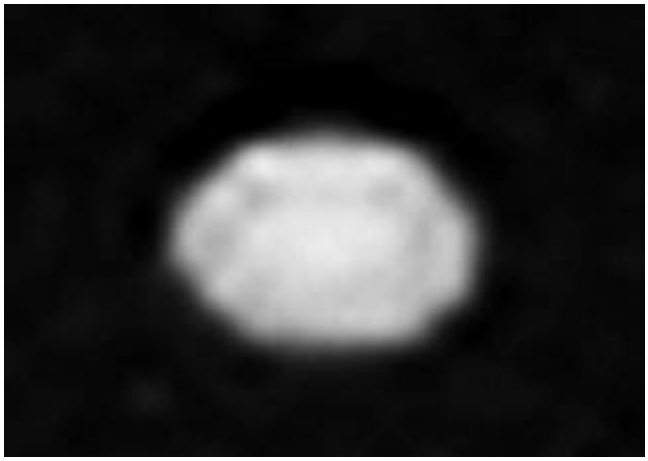
The notion of a "Planet X" has persisted, because over the decades since 1930, it became increasingly clear that Pluto has insufficient mass to account for the observational discrepancies. When *Voyager 2* flew-by Neptune, it took very precise measurements of Neptune's mass. Neptune was evaluated at 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.

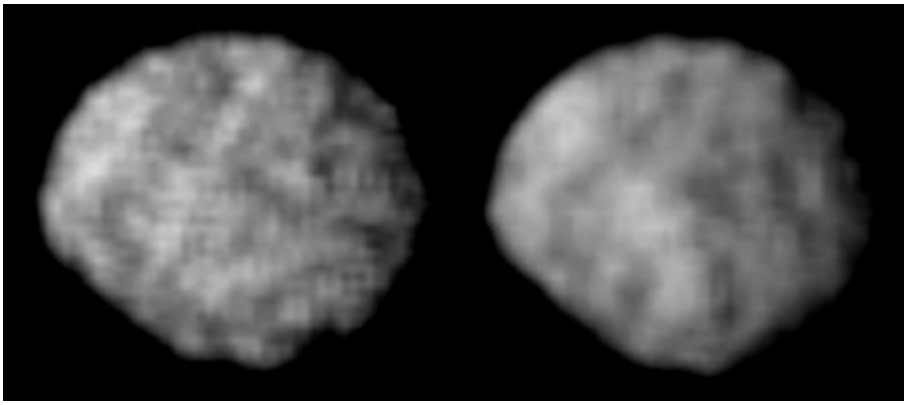


*Voyager 2* image of Neptune

Neptune and Triton three days after *Voyager 2* flyby



Despina as imaged from *Voyager 2*



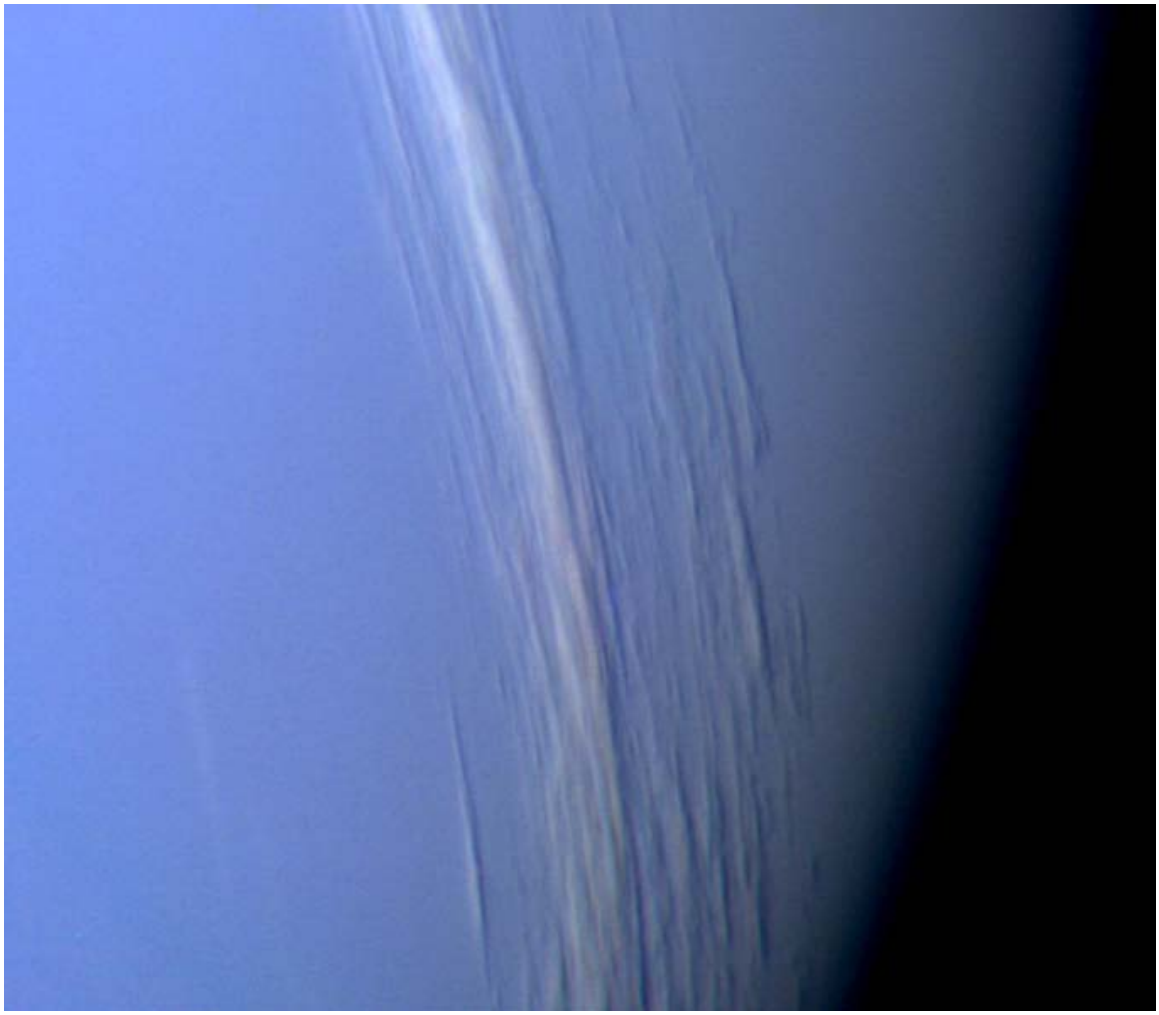
Cratered surface of Larissa

## Interstellar mission

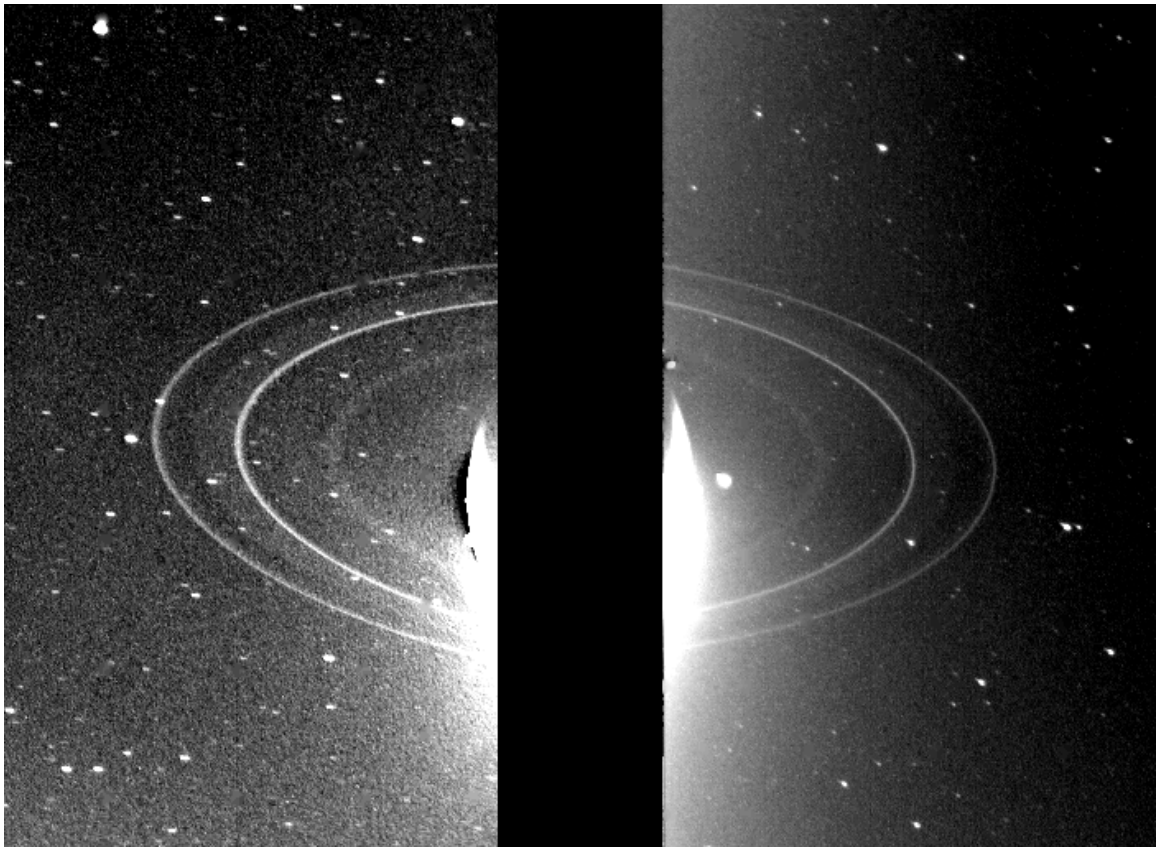
Since its planetary mission is over, *Voyager 2* is now described as working on an interstellar mission, which NASA is using to find out what the solar system is like beyond the heliosphere. On August 30, 2007, *Voyager 2* passed the termination shock into the heliosheath, approximately 1 billion miles (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.

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.

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.

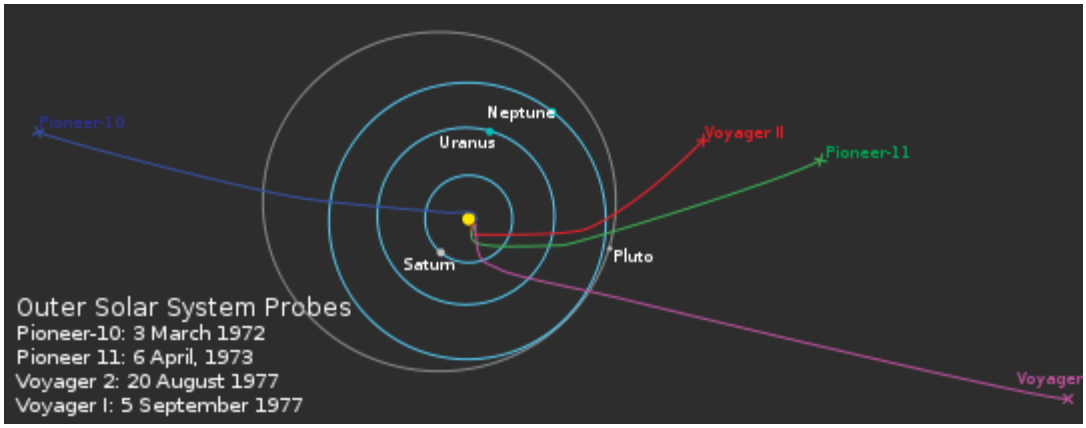
*Voyager 2* is not headed toward any particular star. If left alone, it should pass by star Sirius, which is currently about 2.6 parsecs from the Sun and moving diagonally towards the Sun, at a distance of 1.32 parsecs (4.3 ly, 25 trillion mi) in about 296,000 years.

*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 **February 22nd 2011**, *Voyager 2* is 94.619AU from the Sun, at −54.88° declination and 19.879 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.