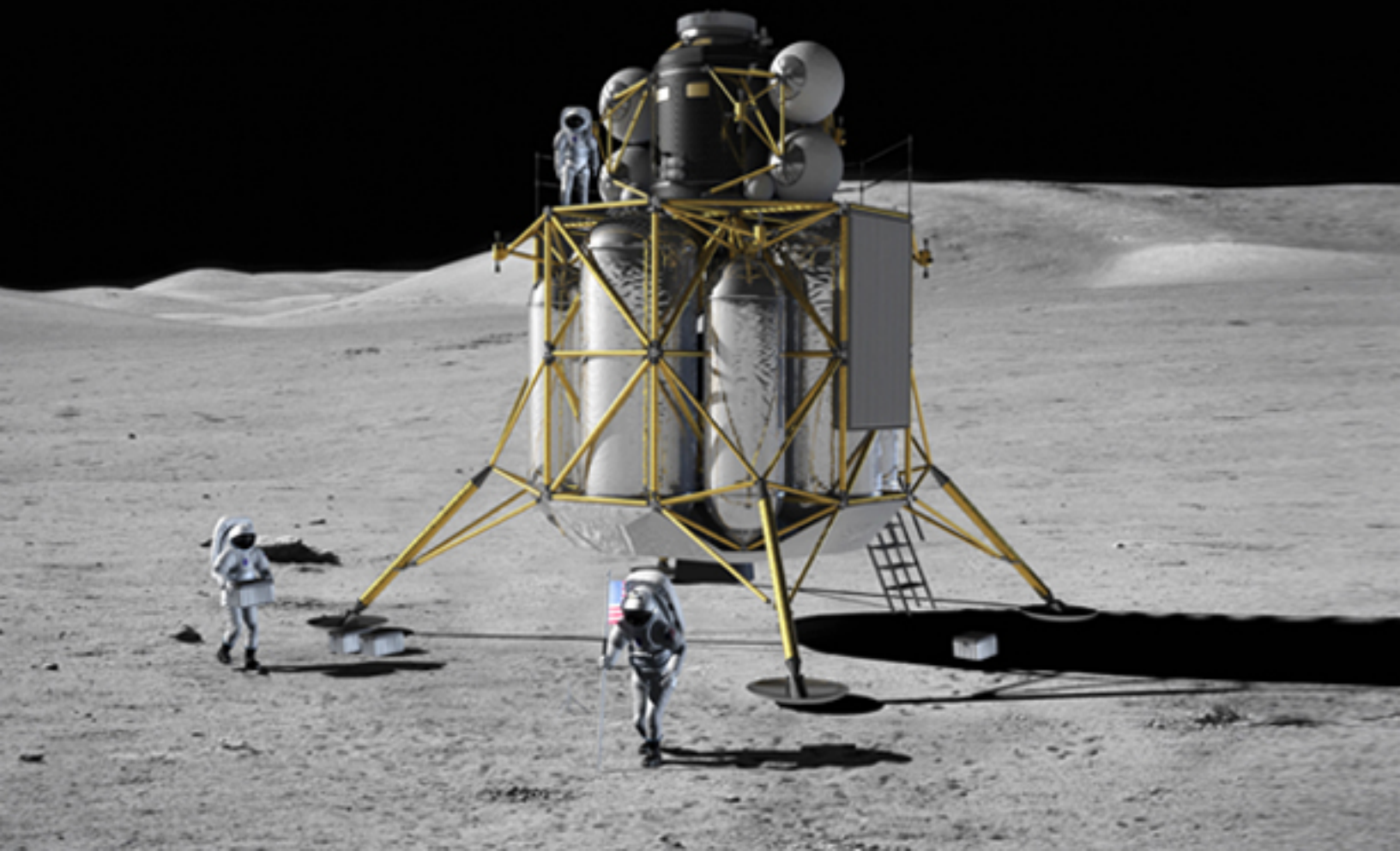


Handbook of
Past and Active
Space Exploration Missions

Pranav Ashley
Nita Lipscomb



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Chapter 1

Magellan (Spacecraft)

Magellan



Artist depiction of Magellan at Venus.

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

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



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

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

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

Mission overview

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

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

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

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

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

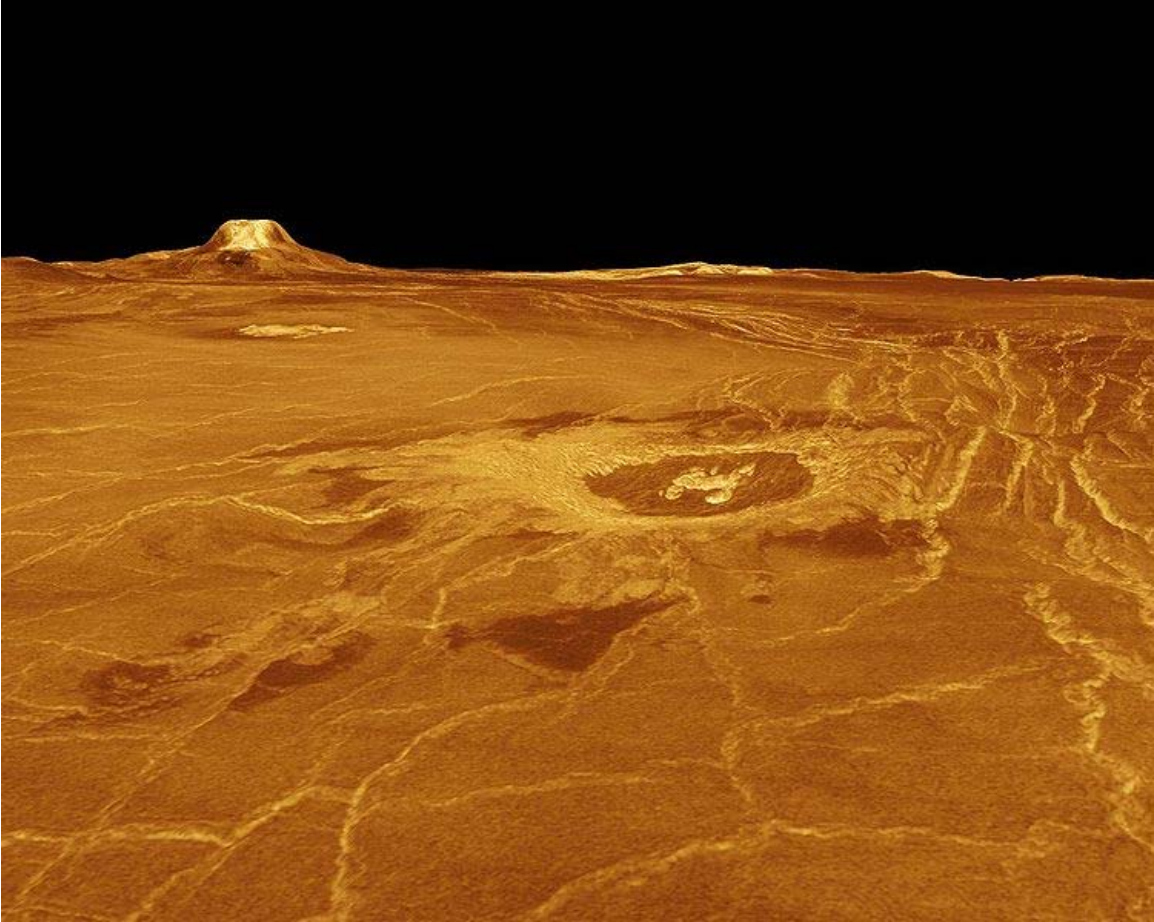
At the end of Magellan's fourth orbital cycle in May 1993, flight controllers circularized the spacecraft's orbit using a then-untried technique called aerobraking. This maneuver sent Magellan dipping into Venus' atmosphere once every orbit; the atmospheric drag on the spacecraft slowed down Magellan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

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

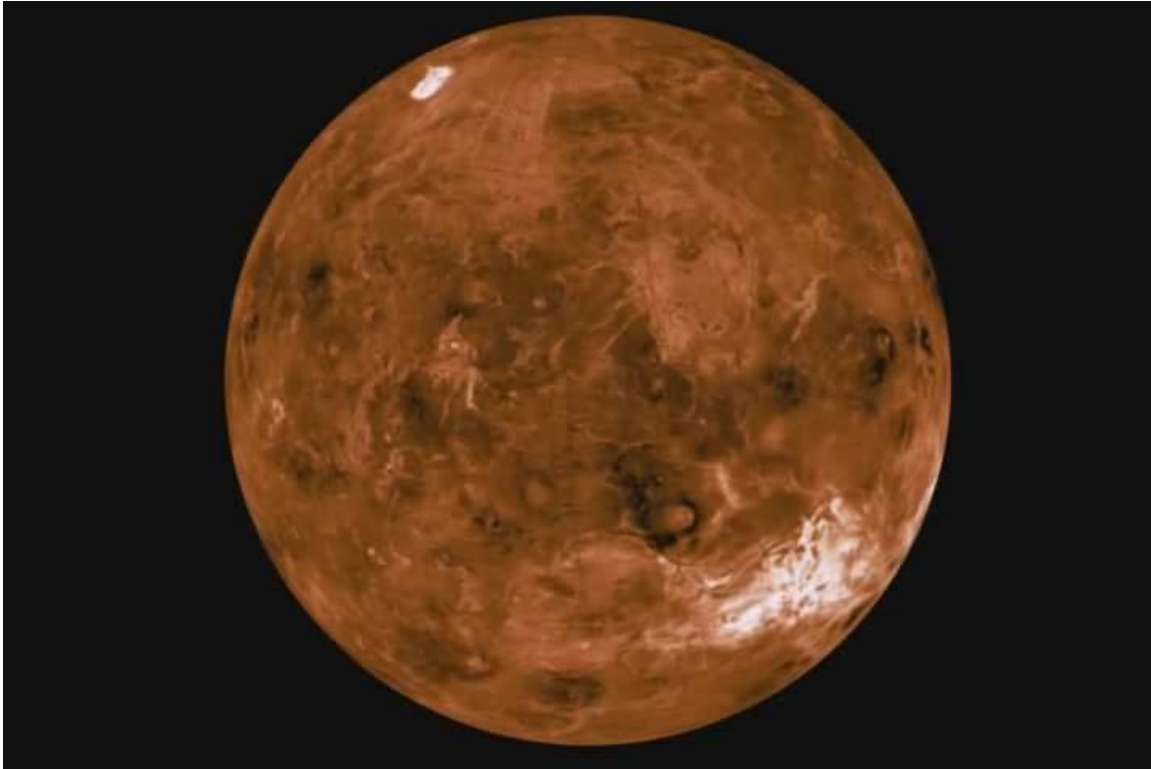
In September 1994, Magellan's orbit was lowered once more in another test called a "windmill experiment". In this test, the spacecraft's solar panels were turned to a configuration resembling the blades of a windmill, and Magellan's orbit was lowered into the thin outer reaches of Venus' dense atmosphere.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

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

Imaging cycles



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



Rendered image of Venus rotating using data gathered by Magellan

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

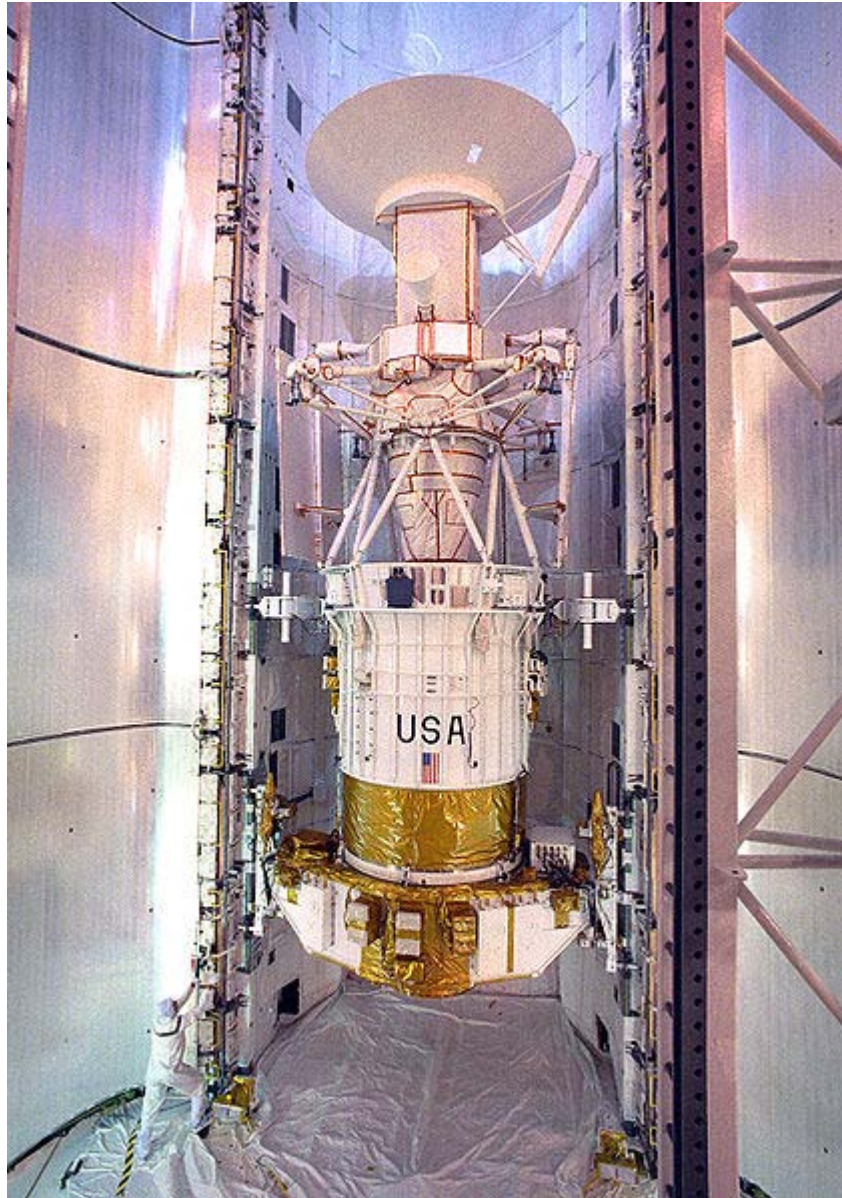
The first images of Venus were received on August 16, 1990, and routine mapping operations began on September 15, 1990. The first mapping cycle (Cycle 1) was completed successfully on May 15, 1991, mapping 84% of the Venusian surface.

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

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

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

Spacecraft design



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

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

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

Magellan was powered by two square solar panels, each measuring 2.5 m (8.2 ft) on a side; together they supplied 1,200 watts of power (100 watt per m²). Over the course of the mission the solar panels gradually degraded, as expected; by the end of the mission in the fall of 1994 it was necessary to manage power usage carefully to keep the spacecraft operating.

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

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

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

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

Mission results

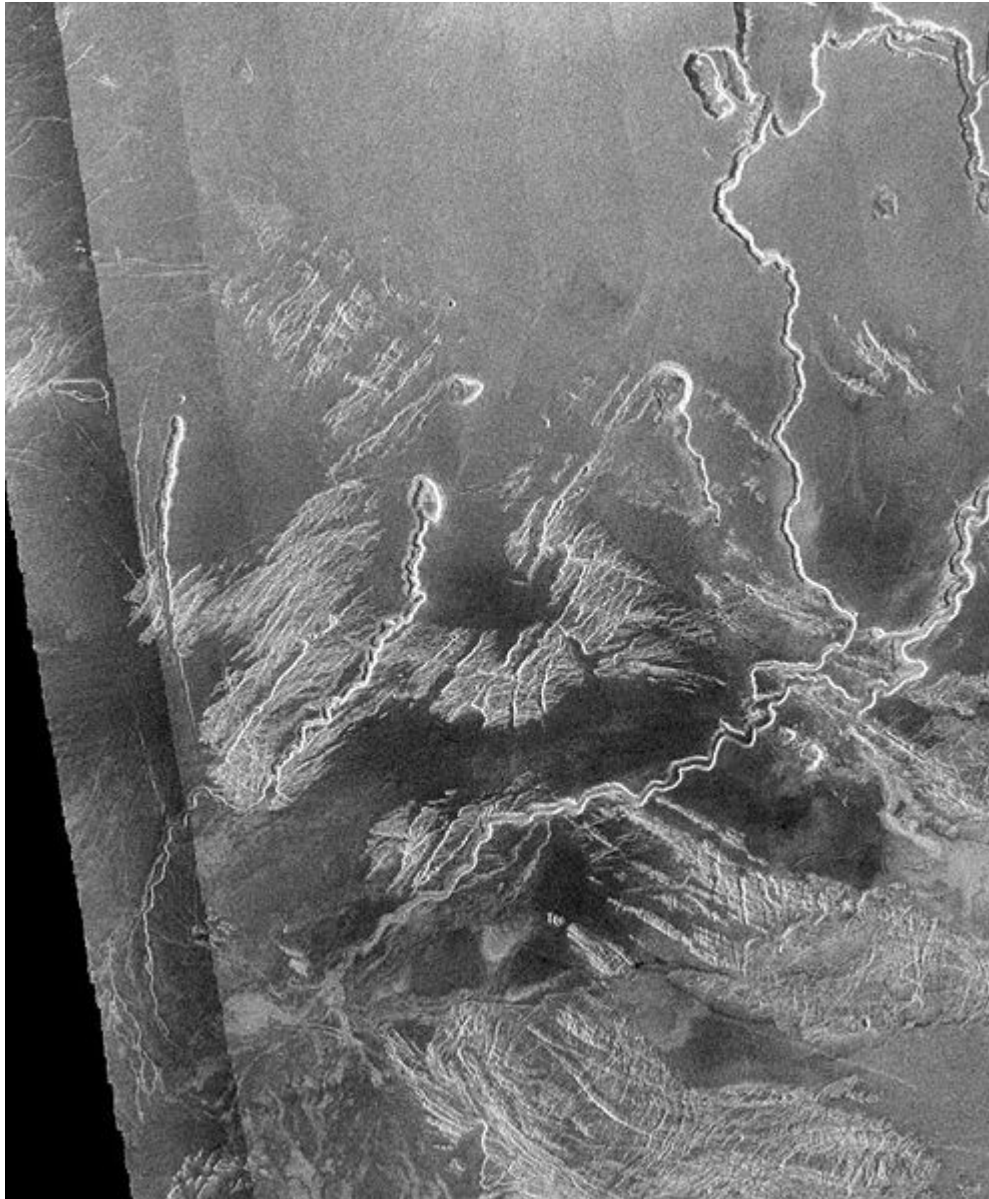


Image of the surface of Venus taken by the Magellan spacecraft

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

shaped volcanic domes suggest the presence of a type of lava produced by extensive evolution of crustal rocks.

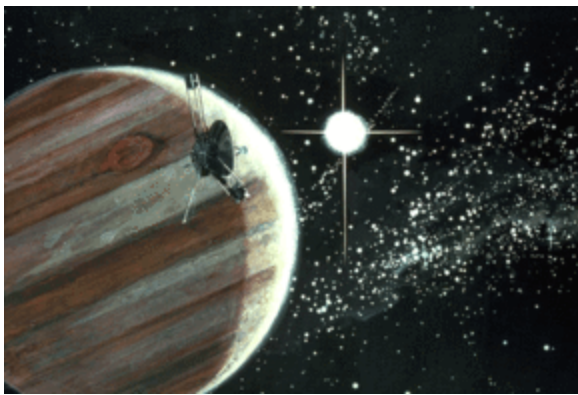
The typical signs of terrestrial plate tectonics - continental drift and basin floor spreading - are not in evidence on Venus. The planet's tectonics is dominated by a system of global rift zones and numerous broad, low domical structures called coronae, produced by the upwelling and subsidence of magma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

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

Chapter 2

Pioneer 10

Pioneer 10



An artist's concept of the Pioneer 10 Jupiter encounter

Operator	ARC / NASA
Major contractors	TRW
Mission type	Flyby
Flyby of	Jupiter
Launch date	1972-03-02 01:49:00 UTC (38 years, 11 months, and 15 days ago)
Launch vehicle	Atlas/Centaur/TE364-4
Launch site	Space Launch Complex 36A Cape Canaveral Air Force Station
Mission duration	Mar 2, 1972 - Jan 23, 2003 (30 years, 10 months, 22 days) (lost communication) Jupiter flyby (completed 1974-01-01)

Interstellar mission

(completed 1997-03-31)

COSPAR ID	1972-012A
Homepage	Pioneer Project website ^(archived) NASA Archive page
Mass	258 kg (569 lb)
Power	165.0 W (4 SNAP-19 RTGs)

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

Mission background

History

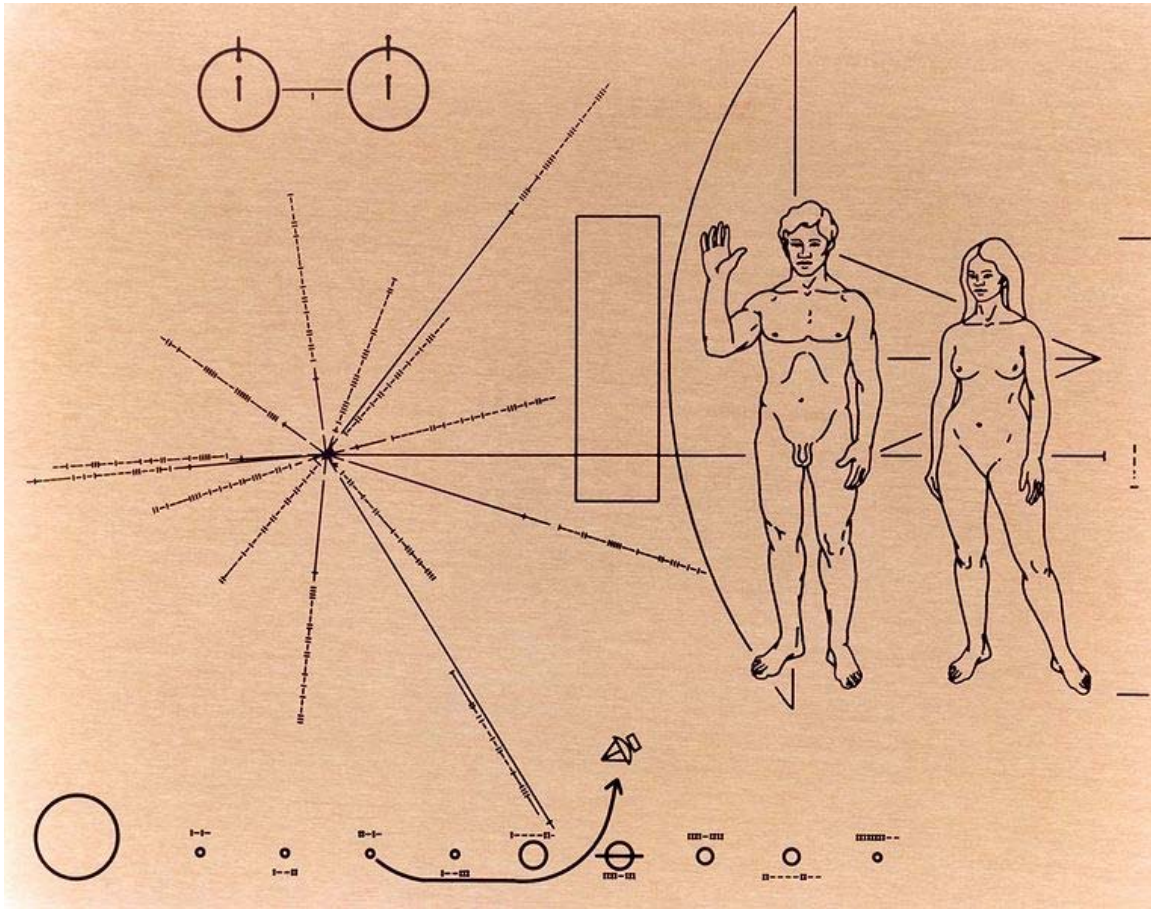
Approved in February 1969, *Pioneer 10* and twin probe *Pioneer 11*, were the first to be designed for exploring the outer solar system. Yielding to multiple proposals throughout the 1960s, early mission objectives were defined as:

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

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

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

Pioneer plaque

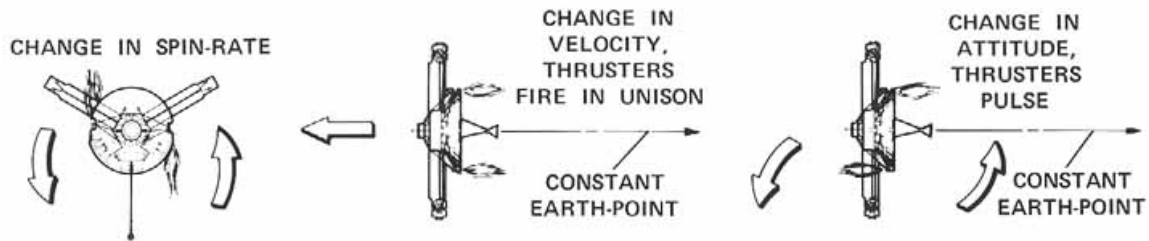


Pioneer 10 and Pioneer 11 carry a gold-anodized aluminium plaque in the event that either spacecraft is ever found by intelligent life-forms from other planetary systems. The plaques feature the nude figures of a human male and female along with several symbols that are designed to provide information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

Spacecraft design

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

Attitude control and propulsion

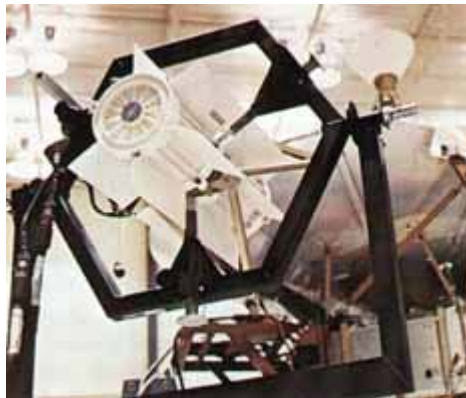


Orientation of the spacecraft was maintained with six 4.5 N, hydrazine monopropellant thrusters: pair one maintained a constant spin-rate of 4.8-rpm, pair two controlled the forward thrust, pair three controlled attitude. Information for the orientation was provided by a star sensor able to reference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

Communications

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

Power



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

Computer

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

Scientific instruments

Helium Vector Magnetometer (HVM)



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

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

Quadrispherical Plasma Analyzer



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

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

Charged Particle Instrument (CPI)



Detects cosmic rays in the Solar System.

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

Cosmic Ray Telescope (CRT)



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

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

Geiger Tube Telescope (GTT)



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

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

Trapped Radiation Detector (TRD)



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

Principal investigator: R. Fillius / University of California San Diego

- **Data:** NSSDC data archive

Meteoroid Detectors



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

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

Asteroid/Meteoroid Detector (AMD)



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

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

Ultraviolet Photometer



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

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

Imaging Photopolarimeter (IPP)



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

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

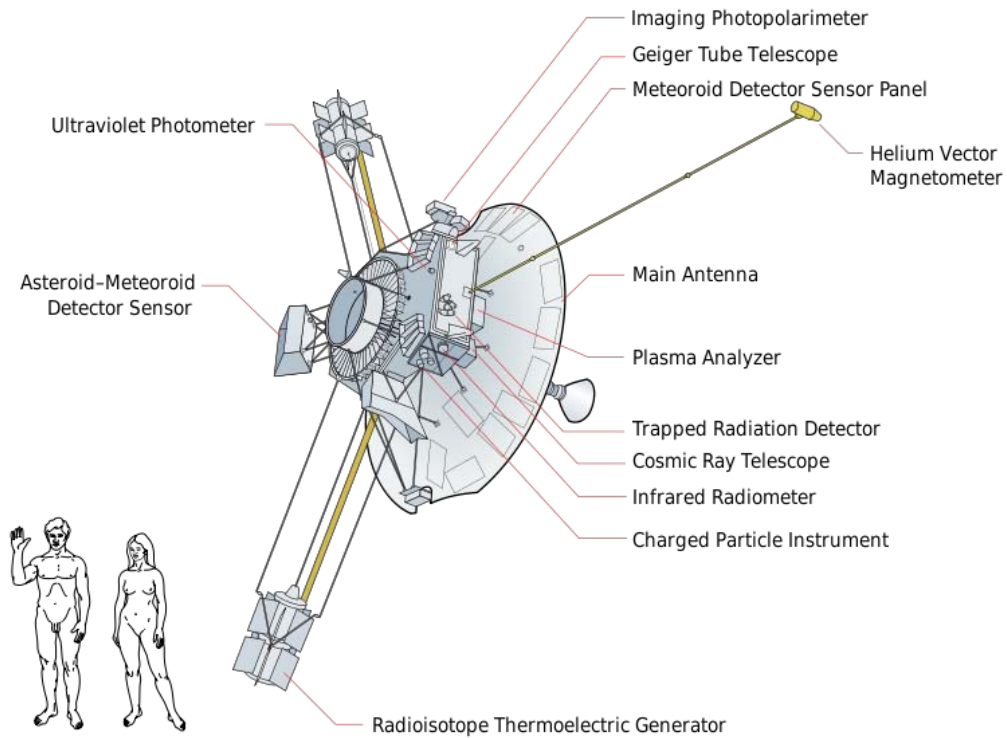
Infrared Radiometer



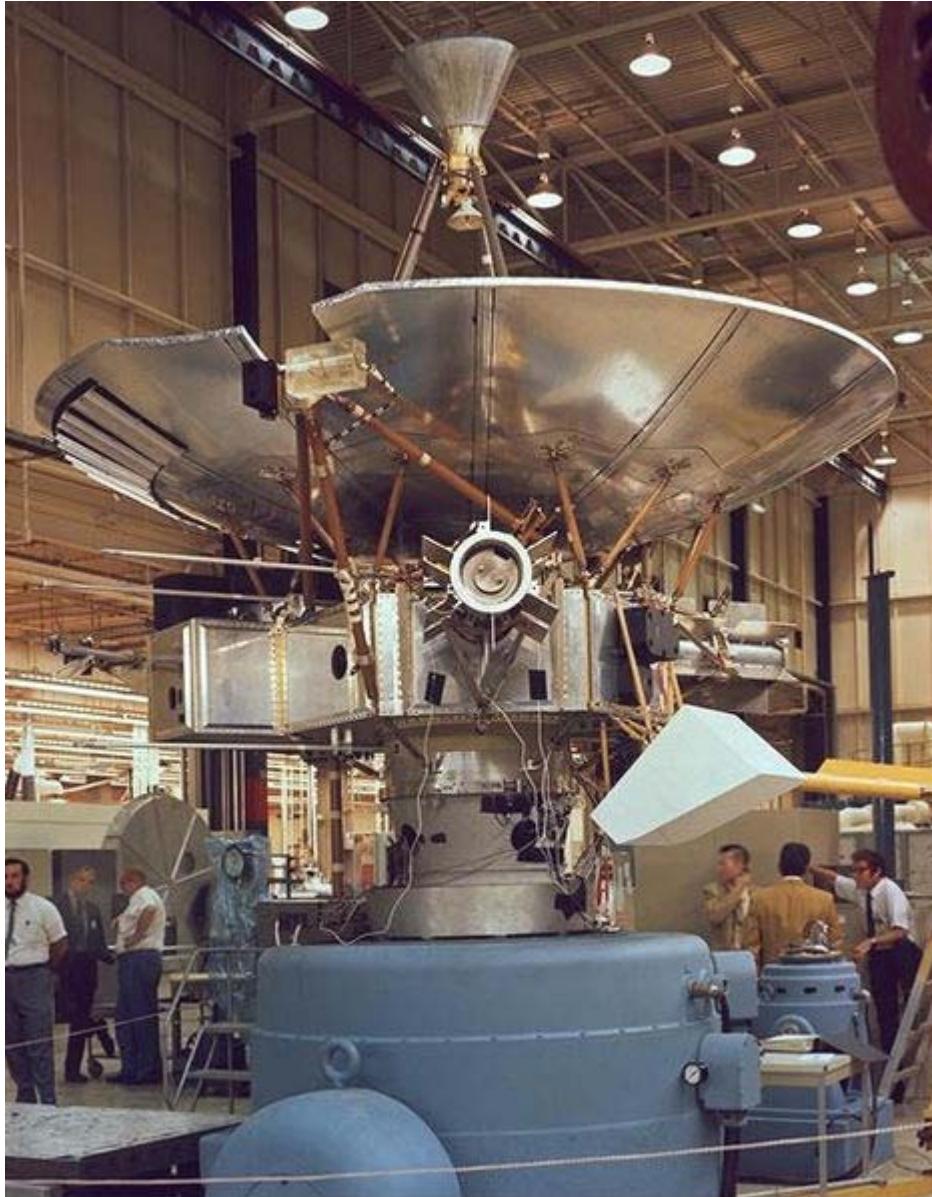
Provides information on cloud temperature and the output of heat from Jupiter.

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

Images of the spacecraft



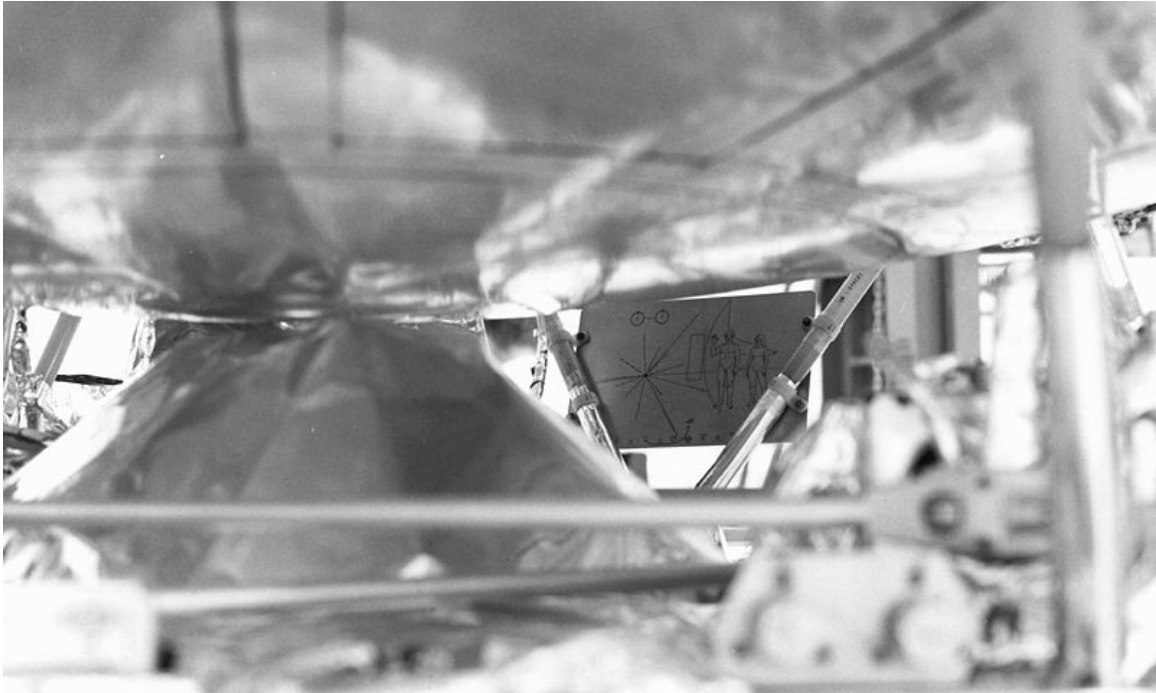
Pioneer 10 and *Pioneer 11* spacecraft diagram



Pioneer 10 in the final stages of construction



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



The Pioneer plaque fixed to the space probe

Mission profile

Timeline of travel

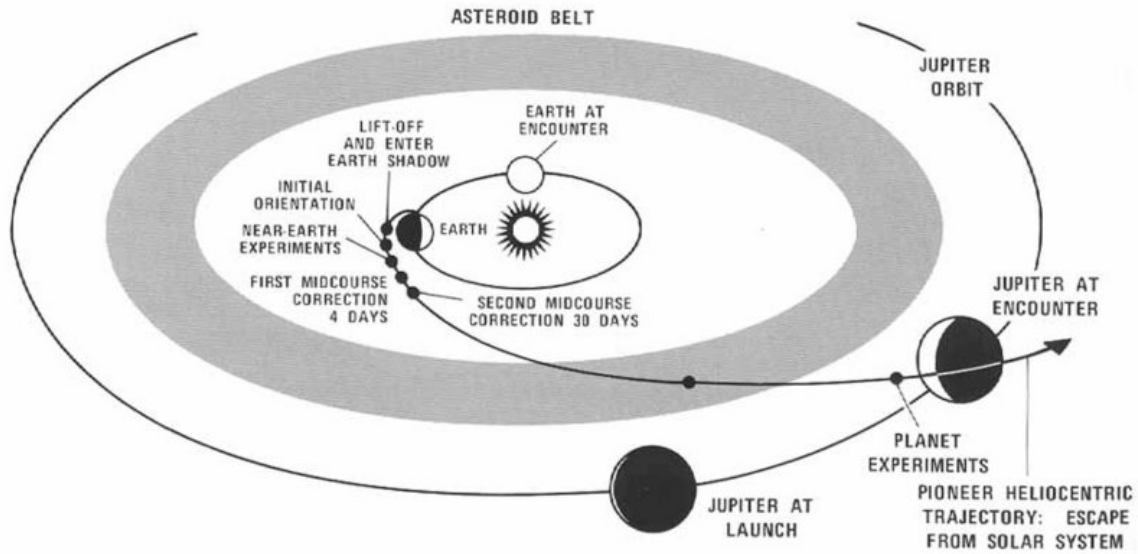
Date	Event
1972-03-03	Spacecraft launched
1972-06-	Crossed orbit of Mars.
1972-07-15	Entered the asteroid belt.
1972-07-15	Start Jupiter observation phase.
	Time Event
1974-01-01	Begin Pioneer Interstellar Mission.

Launch and trajectory

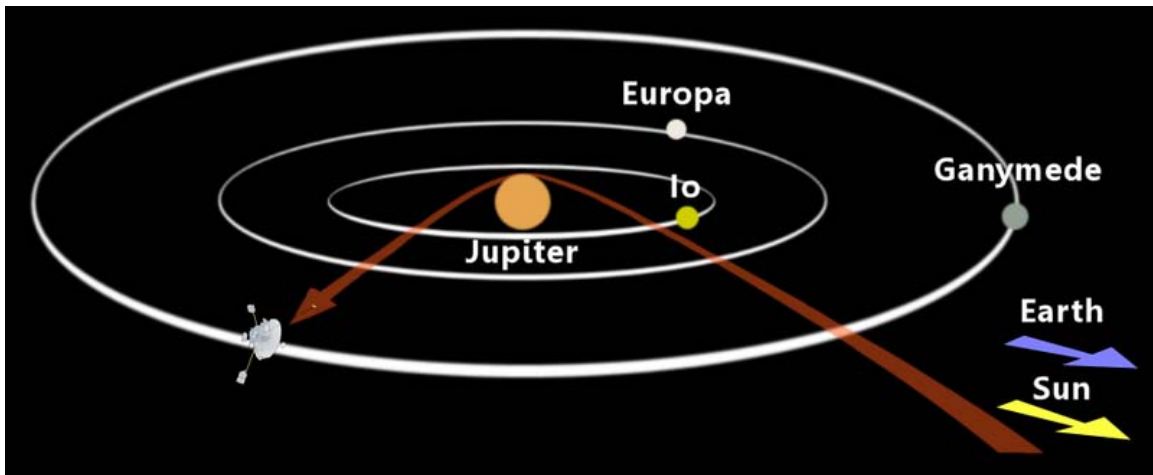
The *Pioneer 10* probe was launched on March 3, 1972 at 01:49:00 UTC by the National Aeronautics and Space Administration from Space Launch Complex 36A at Cape Canaveral, Florida aboard an Atlas/Centaur launch vehicle. The launch vehicle accelerated the probe for 17 minutes, reaching a velocity of 51,682 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)



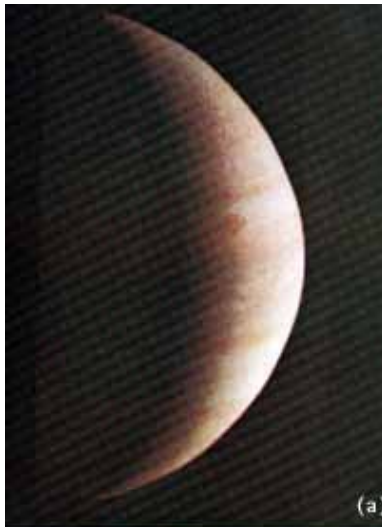
Jupiter encounter (frame 4)



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



Ganymede as seen from *Pioneer 10*



Sunrise on a crescent-shaped Jupiter



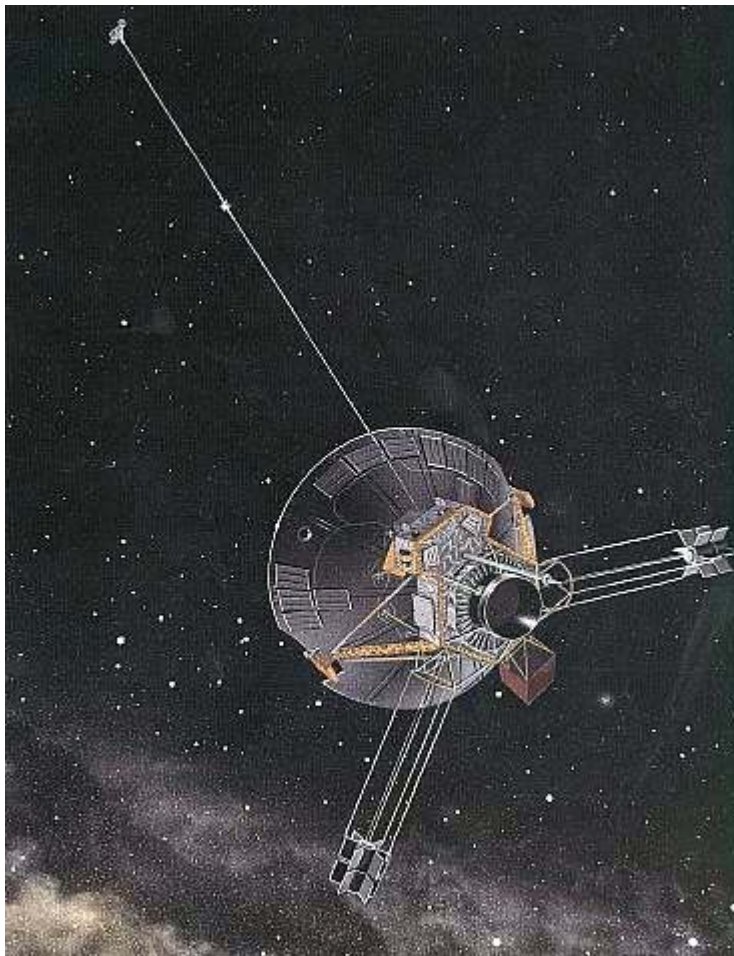
Europa as seen by Pioneer 10

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 $(8.74 \pm 1.33) \times 10^{-10} \text{ m/s}^2$ directed towards the Sun. Although it is suspected that there is a systematic origin to the effect, none has been found. As a result, there is growing interest in the nature of this anomaly.

Current status



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

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

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

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

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

Chapter 3

Voyager 1

Voyager 1



Voyager spacecraft

Operator	NASA / JPL
Mission type	Flyby
Flyby of	Jupiter, Saturn
Launch date	1977-09-05 12:56:00 UTC (33 years, 5 months, and 13 days ago)
Launch vehicle	Titan IIIE / Centaur
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In progress (Interstellar mission) (32 years, 1 month, and 14 days elapsed) Jupiter encounter (completed 1979-04-13)

Saturn encounter

(completed 1980-12-14)

COSPAR ID	1977-084A
Homepage	NASA <i>Voyager</i> website
Mass	721.9 kg (1,592 lb)
Power	420 W (3 RTGs)

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

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

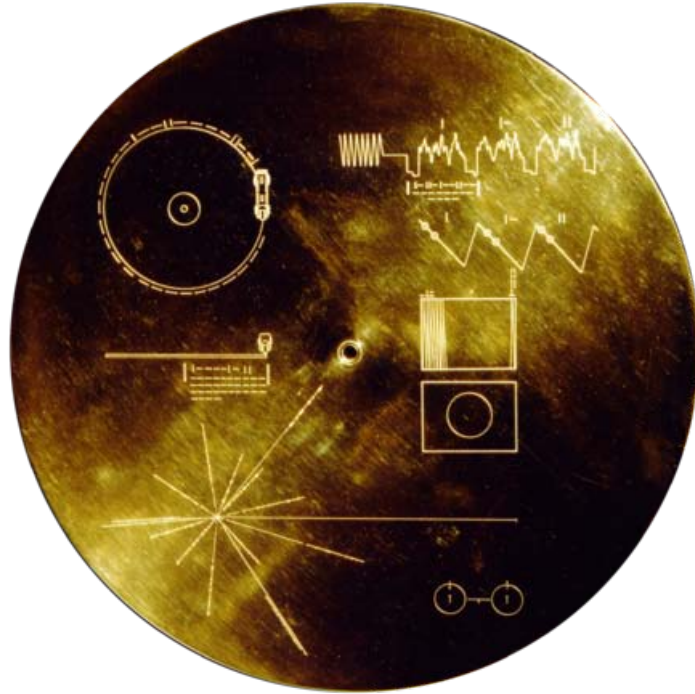
Mission background

History

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

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

Golden record



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

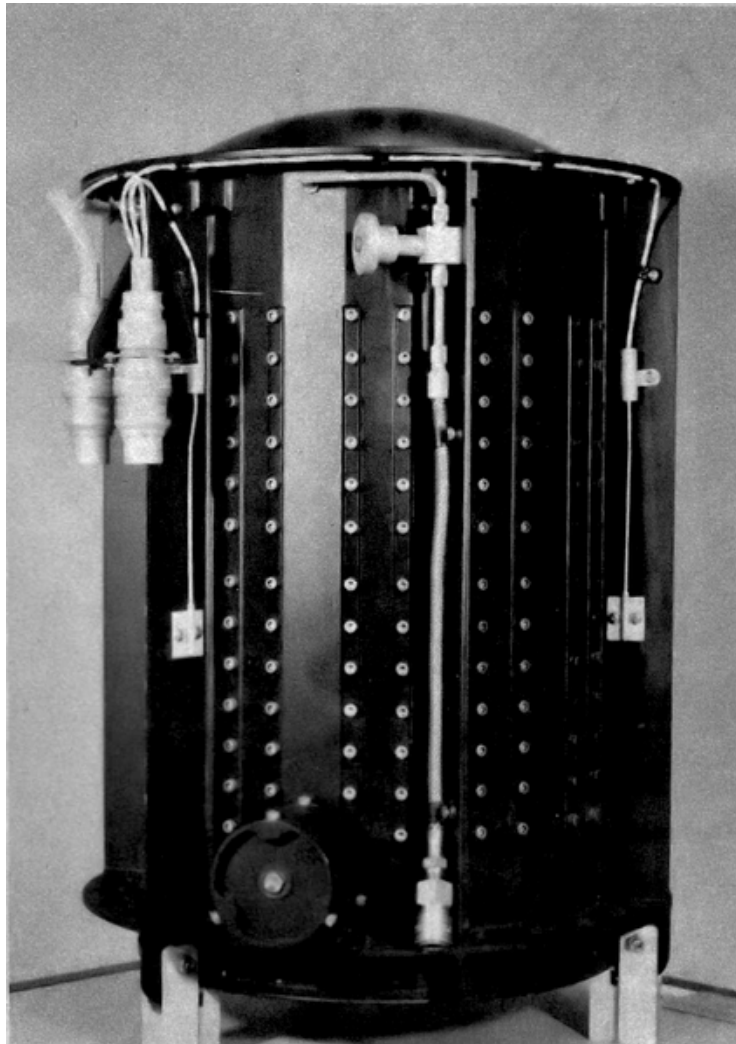
Spacecraft design

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

Communications

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

Power



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

Scientific instruments

Expand

Instrument Name **Abr.** **Description**

Imaging Science System	(ISS)	Utilizes a two-camera system (narrow-angle/wide-angle) to provide imagery of Jupiter, Saturn and other objects along the trajectory.		Wide Angle Camera Filters					
		Narrow Angle Camera Filters			Name	Wavelength	Spectrum	Sensitivity	
		Name	Wavelength	Spectrum	Sensitivity	Clear	280 nm - 640 nm		
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		UV	280 nm - 370 nm			Blue	430 nm - 530 nm		
		Violet	350 nm - 450 nm			CH ₄ -U	536 nm - 546 nm		
		Blue	430 nm - 530 nm			Green	530 nm - 640 nm		
		Green	530 nm - 640 nm			Na-D	588 nm - 590 nm		
		Orange	590 nm - 640 nm			Orange	590 nm - 640 nm		
						CH ₄ -JST	614 nm - 624 nm		

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

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.

Radio Science System
(disabled) (RSS)

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

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.

Infrared Interferometer Spectrometer
(disabled) (IRIS)

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

Designed to measure atmospheric properties, and to measure radiation.

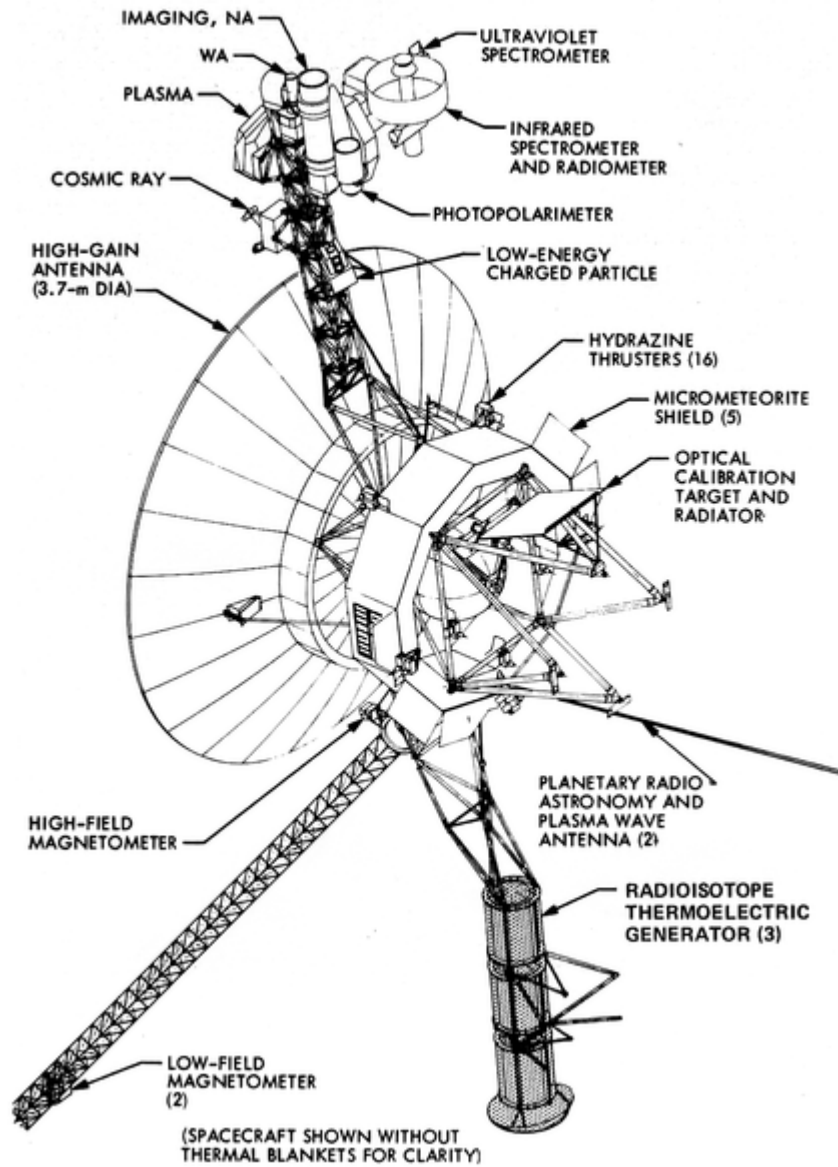
Ultraviolet Spectrometer
(active) (UVS)

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

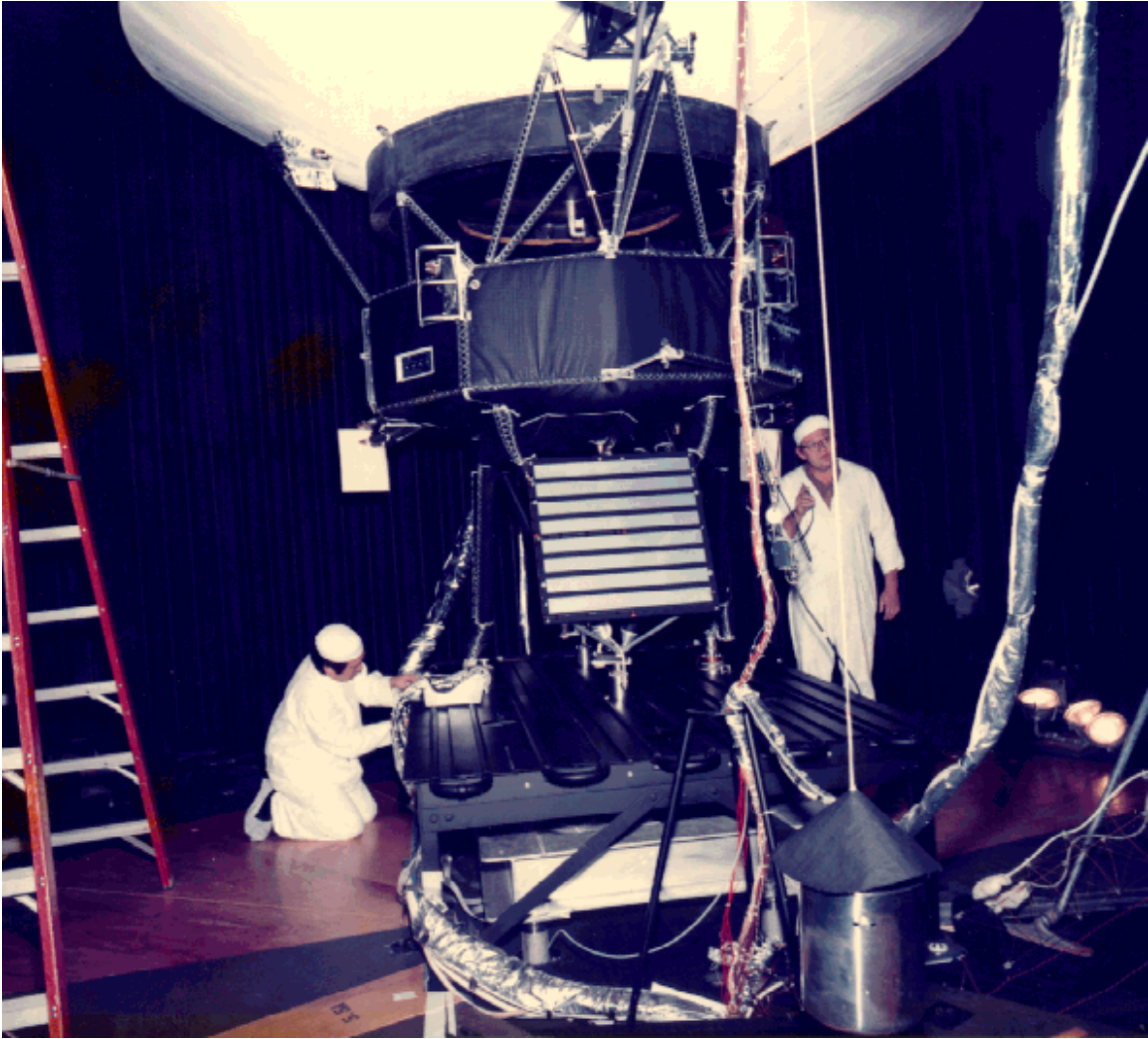
Triaxial Fluxgate (MAG) Designed to investigate the magnetic fields of Jupiter and Saturn, the solar-wind interaction with

Magnetometer (active)		<p>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.</p> <ul style="list-style-type: none"> • Principal investigator: Norman Ness / NASA Goddard Space Flight Center (website) • Data: PDS/PPI data catalog, NSSDC data archive <p>Investigates the macroscopic properties of the plasma ions and measures electrons in the energy range from 5 eV to 1 keV.</p>
Plasma Spectrometer (defective)	(PLS)	<ul style="list-style-type: none"> • Principal investigator: John Richardson / MIT (website) • Data: PDS/PPI data catalog, NSSDC data archive <p>Measures the differential in energy fluxes and angular distributions of ions, electrons and the differential in energy ion composition.</p>
Low Energy Charged Particle Instrument (active)	(LECP)	<ul style="list-style-type: none"> • Principal investigator: Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website) • Data: UMD data plotting, PDS/PPI data catalog, NSSDC data archive <p>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.</p>
Cosmic Ray System (active)	(CRS)	<ul style="list-style-type: none"> • Principal investigator: Edward Stone / CalTech / NASA Goddard Space Flight Center (website) • Data: PDS/PPI data catalog, NSSDC data archive <p>Utilizes a sweep-frequency radio receiver to study the radio-emission signals from Jupiter and Saturn.</p>
Planetary Radio Astronomy Investigation (disabled)	(PRA)	<ul style="list-style-type: none"> • Principal investigator: James Warwick / University of Colorado • Data: PDS/PPI data catalog, NSSDC data archive <p>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.</p>
Photopolarimeter System (defective)	(PPS)	<ul style="list-style-type: none"> • Principal investigator: Arthur Lane / JPL (PDS/PRN website) • Data: PDS/PRN data catalog <p>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.</p>
Plasma Wave System (partially disabled)	(PWS)	<ul style="list-style-type: none"> • Principal investigator: Donald Gurnett / University of Iowa (website) • Data: PDS/PPI data catalog, NSSDC data archive

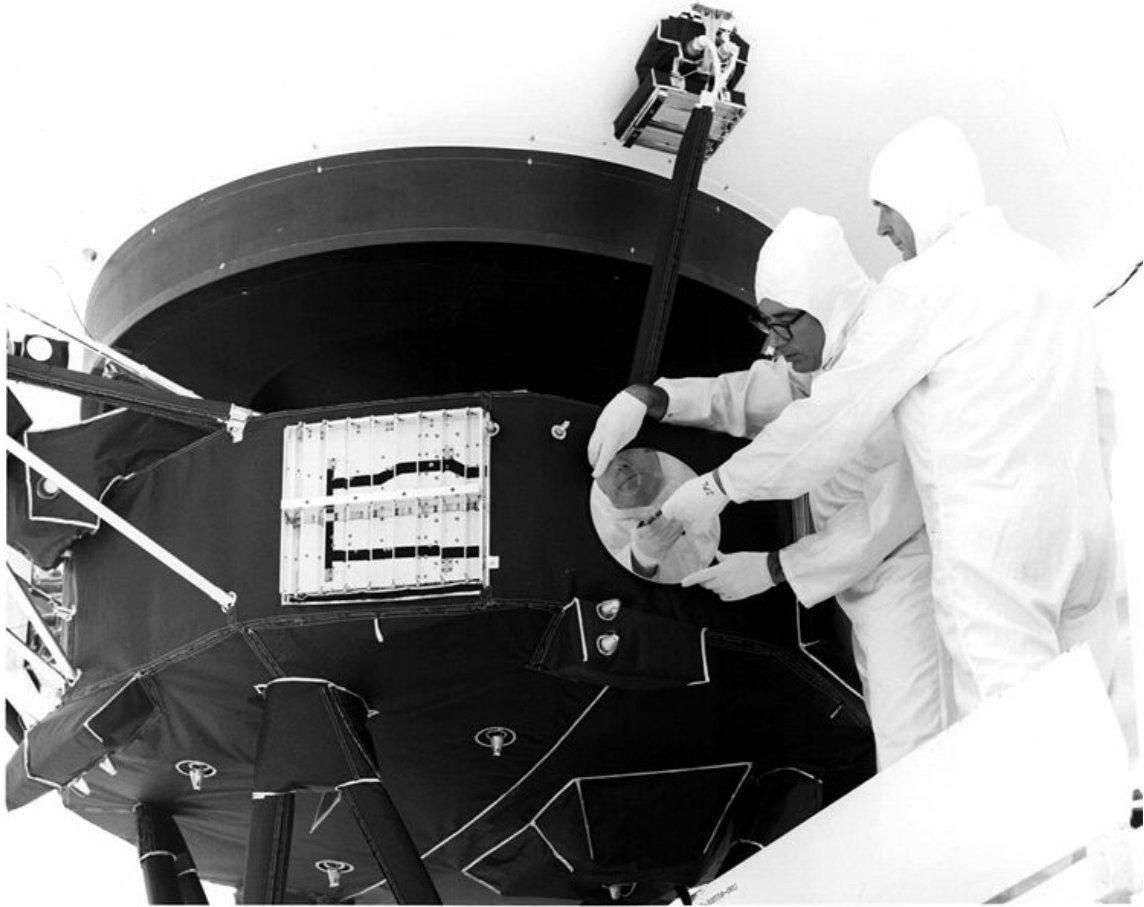
Images of the spacecraft



Voyager spacecraft diagram



Voyager 1 in a space simulator chamber



Gold-Plated Record is attached to *Voyager 1*



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

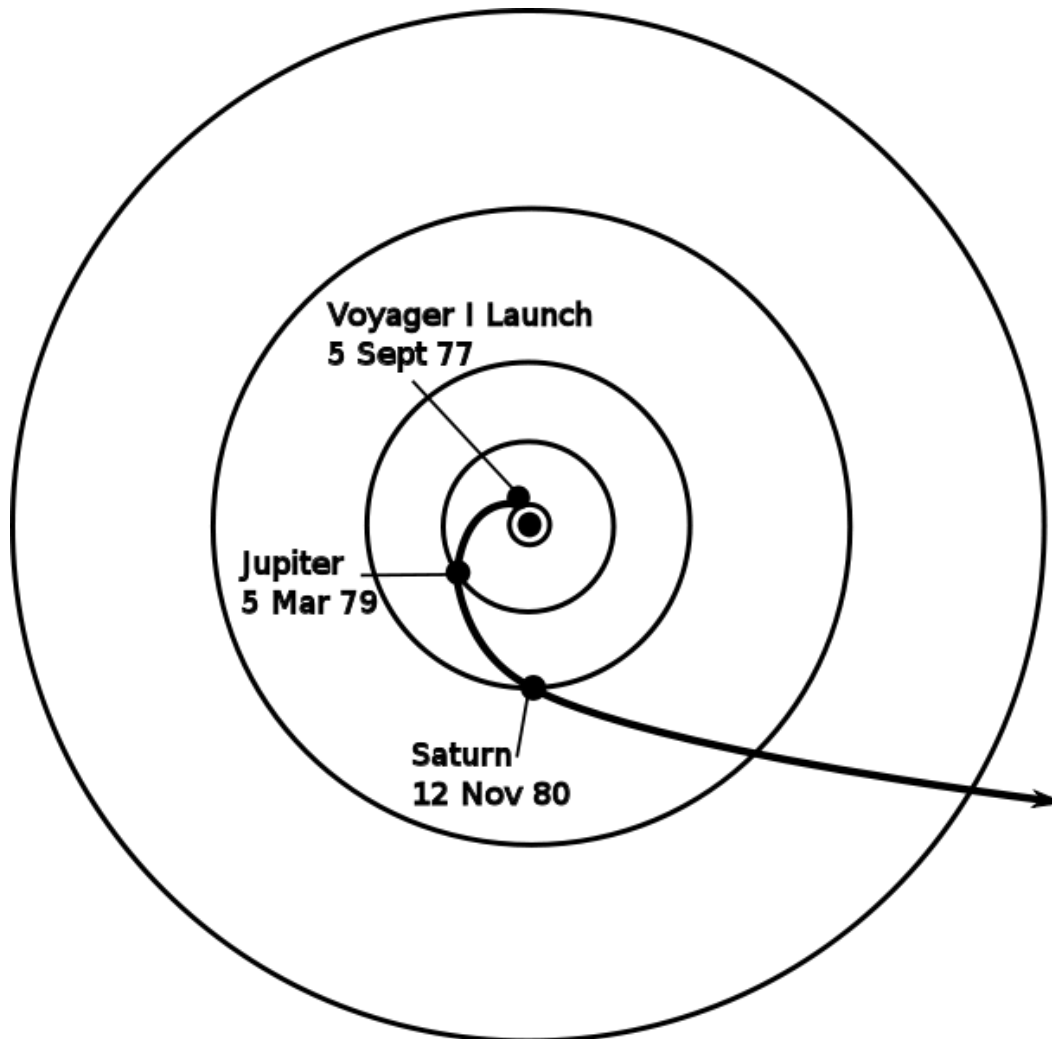
Mission profile

Launch and trajectory

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



Voyager 1 lifted off with a Titan IIIE/Centaur

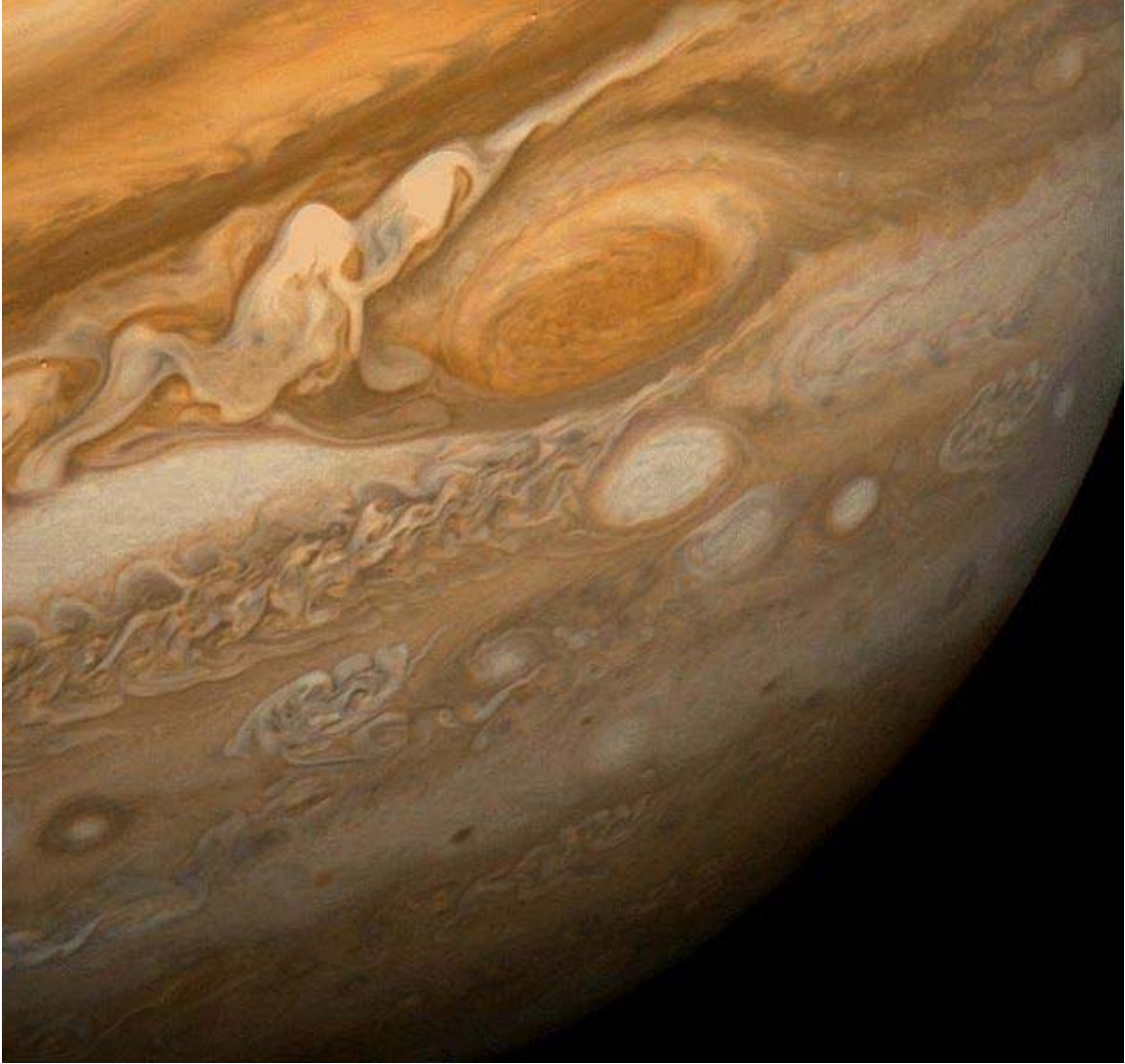


Trajectory of *Voyager 1* primary mission

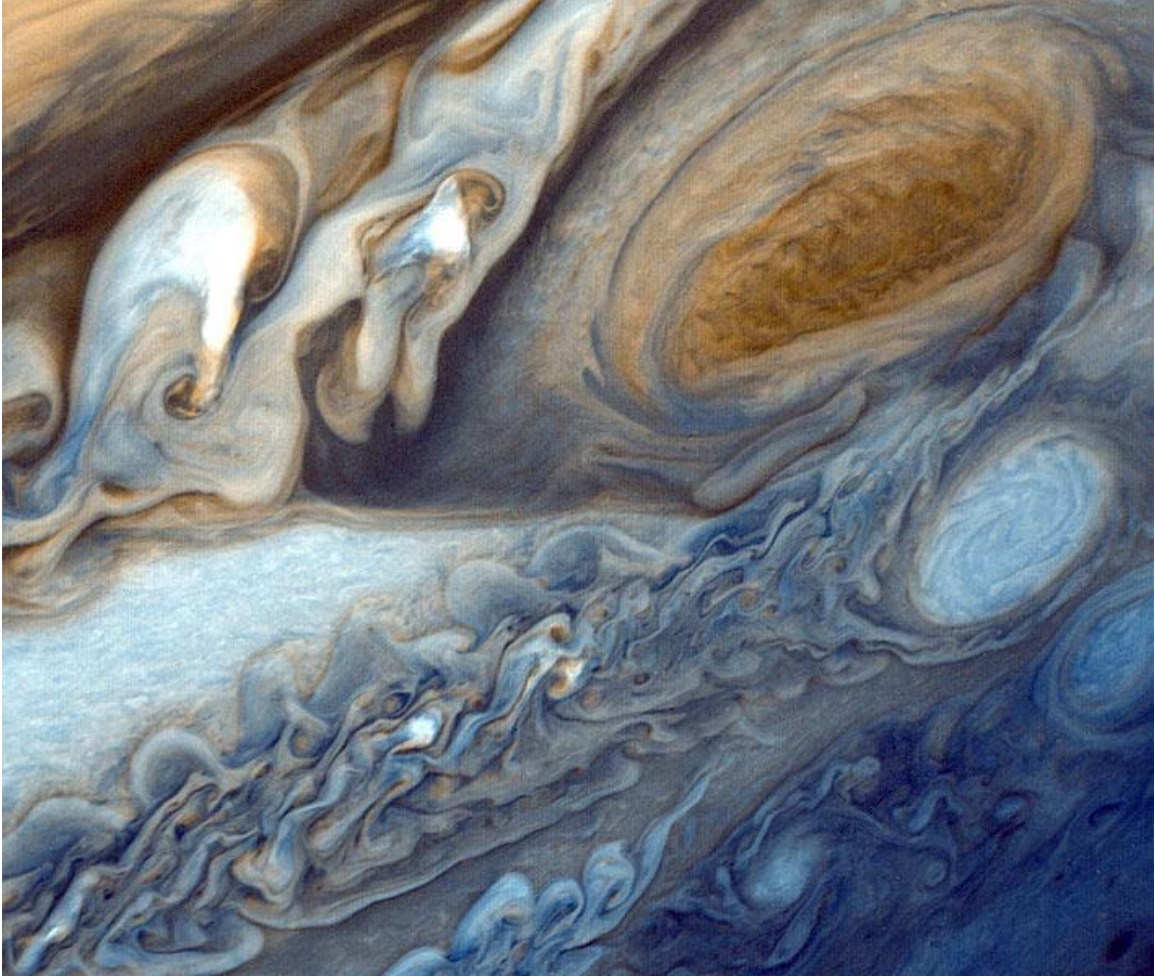
Encounter with Jupiter

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

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



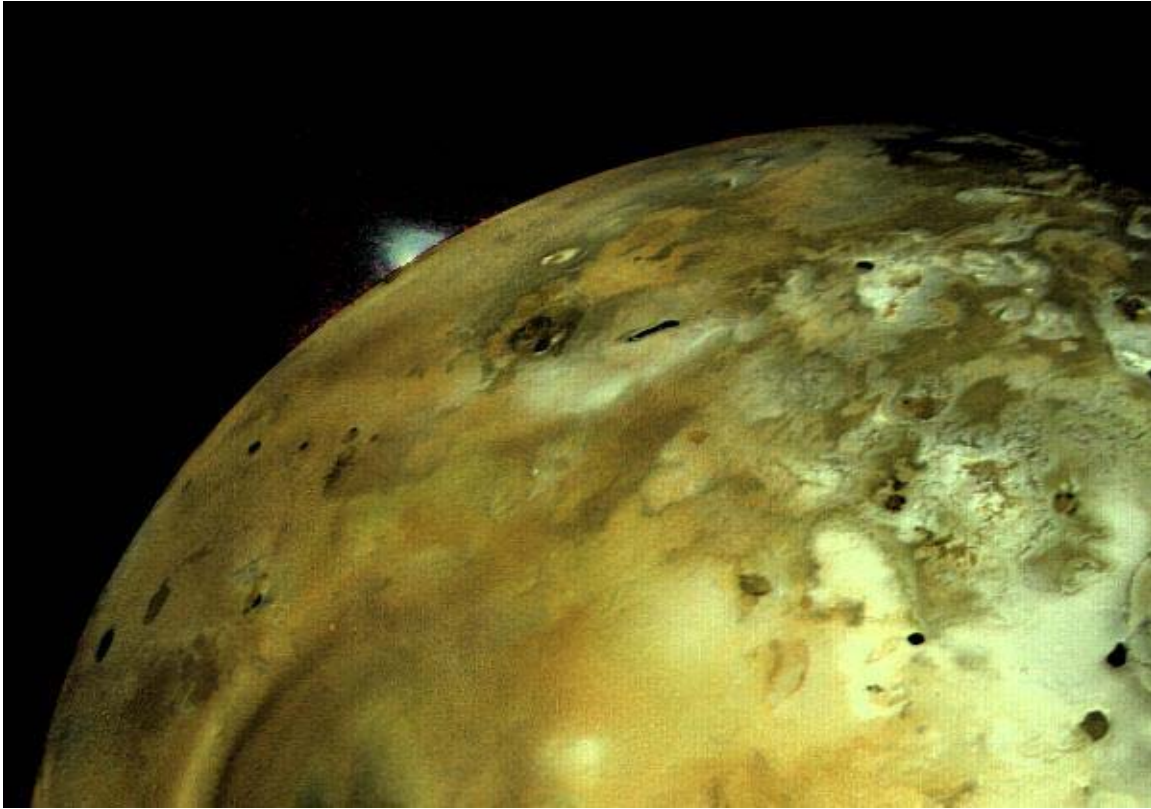
The Great Red Spot as seen from *Voyager 1*



False color detail of Jupiter's atmosphere



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



Volcanic eruption on Io photographed from *Voyager 1*

Encounter with Saturn

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

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

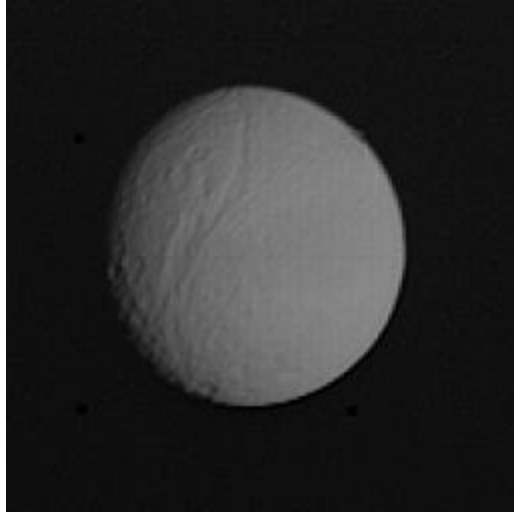
Its trajectory with a close fly-by of Titan caused an extra gravitational deflection that sent *Voyager 1* out of the plane of the Ecliptic, thus ending its planetary science mission. *Voyager 1* could have been commanded onto a different trajectory, whereby the gravitational slingshot effect of Saturn's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



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



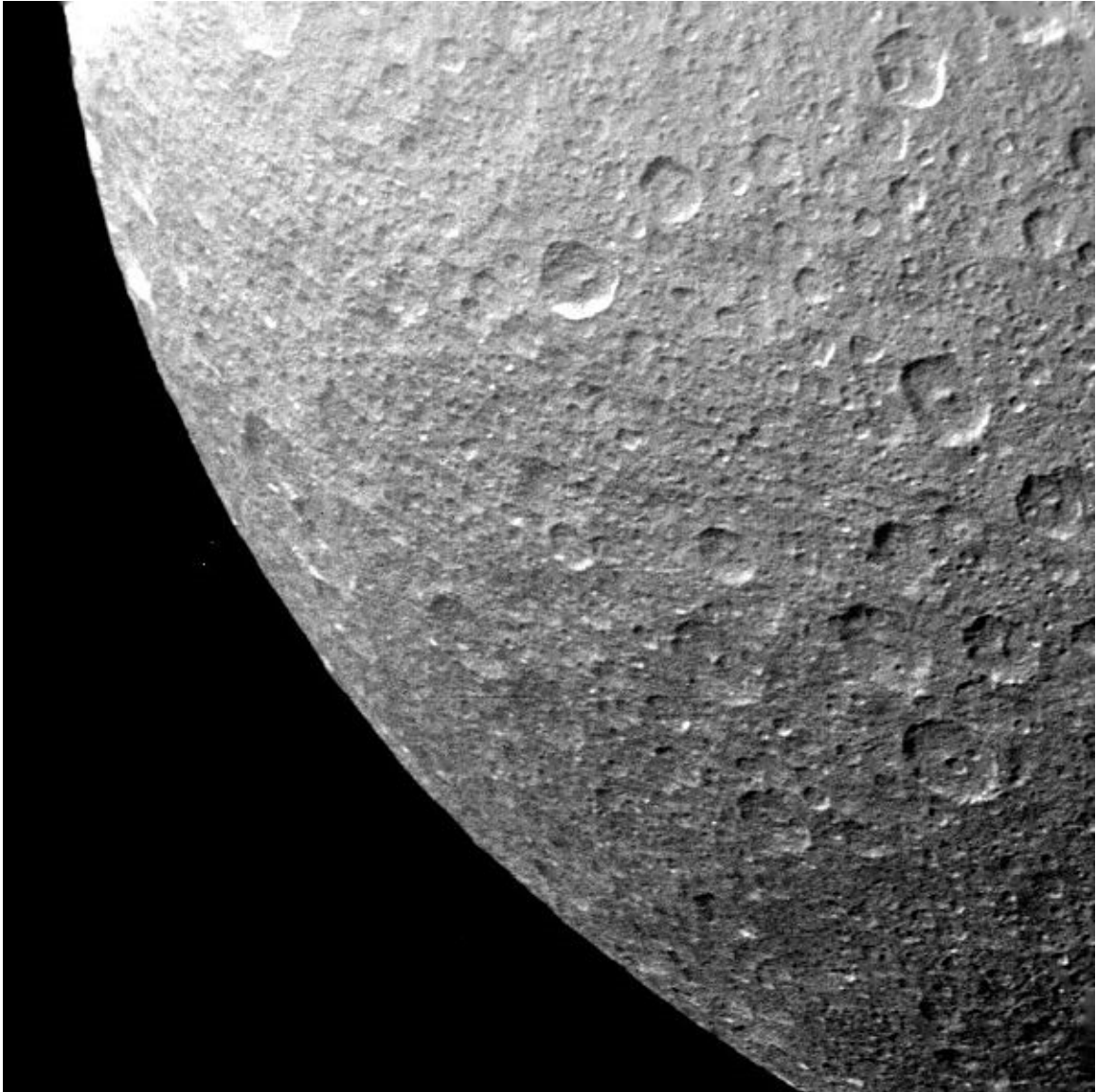
Mimas at a range of 425,000 km from *Voyager 1*



Tethys photographed by *Voyager 1* from 1.2 million km



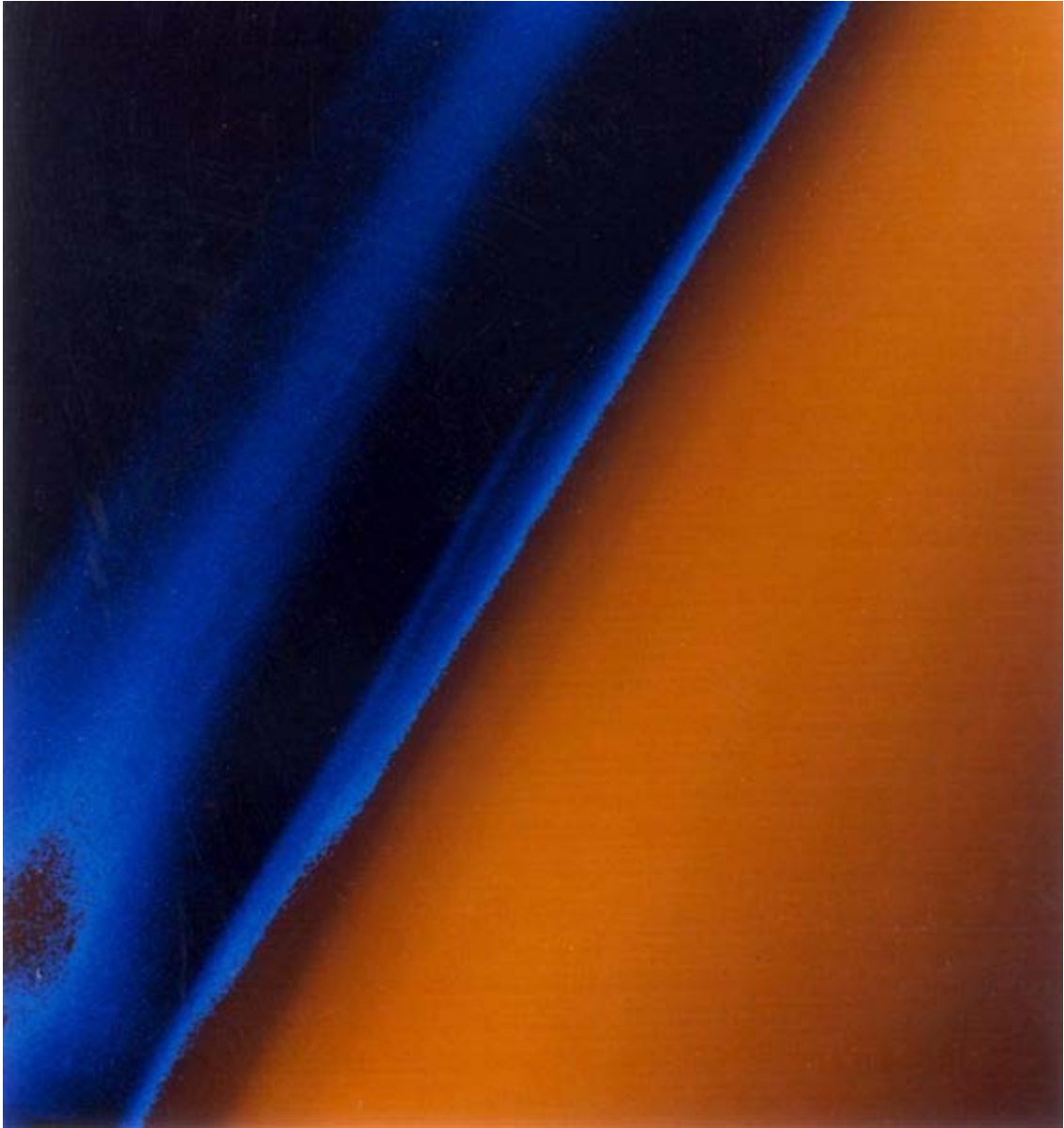
Fractured terrain on Dione



Impact craters on the surface of Rhea appear similar to Mercury



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

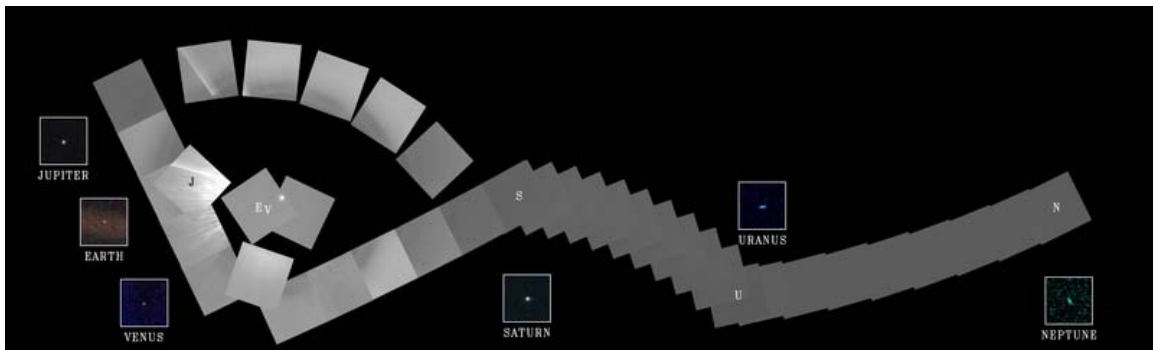


Layers of haze covering Saturn's satellite Titan



Voyager 1 image of Saturn's F Ring

Interstellar mission



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

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

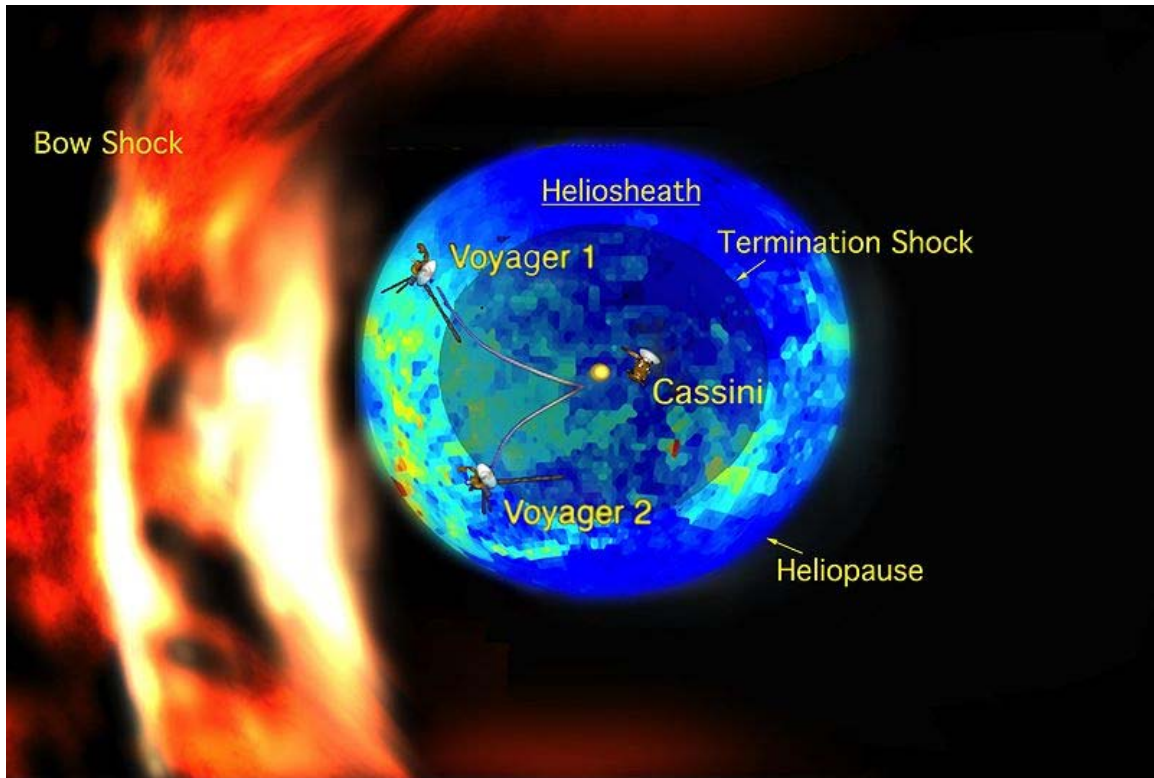
On November 17, 1998, *Voyager 1* overtook *Pioneer 10* as the most distant man-made object from Earth, at a distance of 69.419 AU. It is currently the most distant functioning

space probe to receive commands and transmit information to Earth. Provided *Voyager 1* does not collide with any stellar objects, the *New Horizons* space probe will never pass it, despite being launched from Earth at a faster speed than either *Voyager* spacecraft.

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

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

Heliopause



Voyager 1 is currently within the heliosheath and approaching interstellar space

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

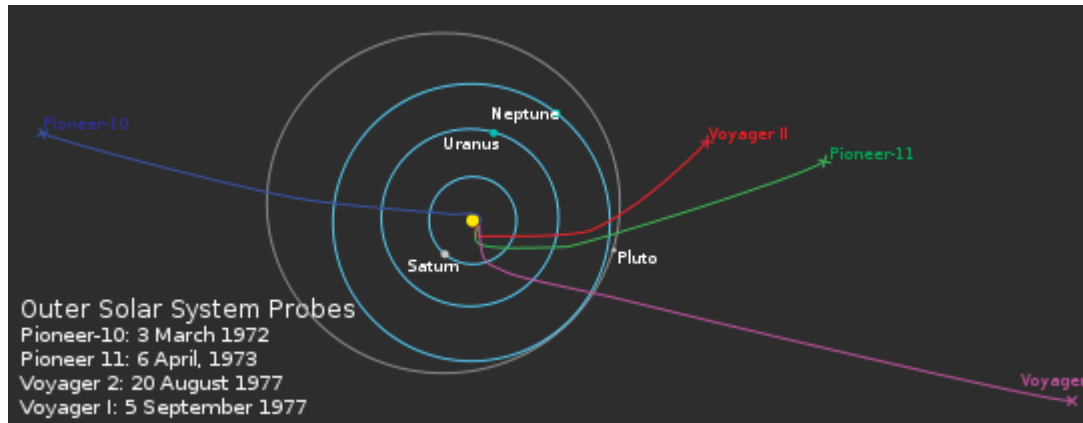
Scientists at the Johns Hopkins University Applied Physics Laboratory believe that *Voyager 1* entered the termination shock in February 2003. Some other scientists have expressed doubt, discussed in the journal *Nature* of November 6, 2003. In a scientific session at the American Geophysical Union meeting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

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

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

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

Current status

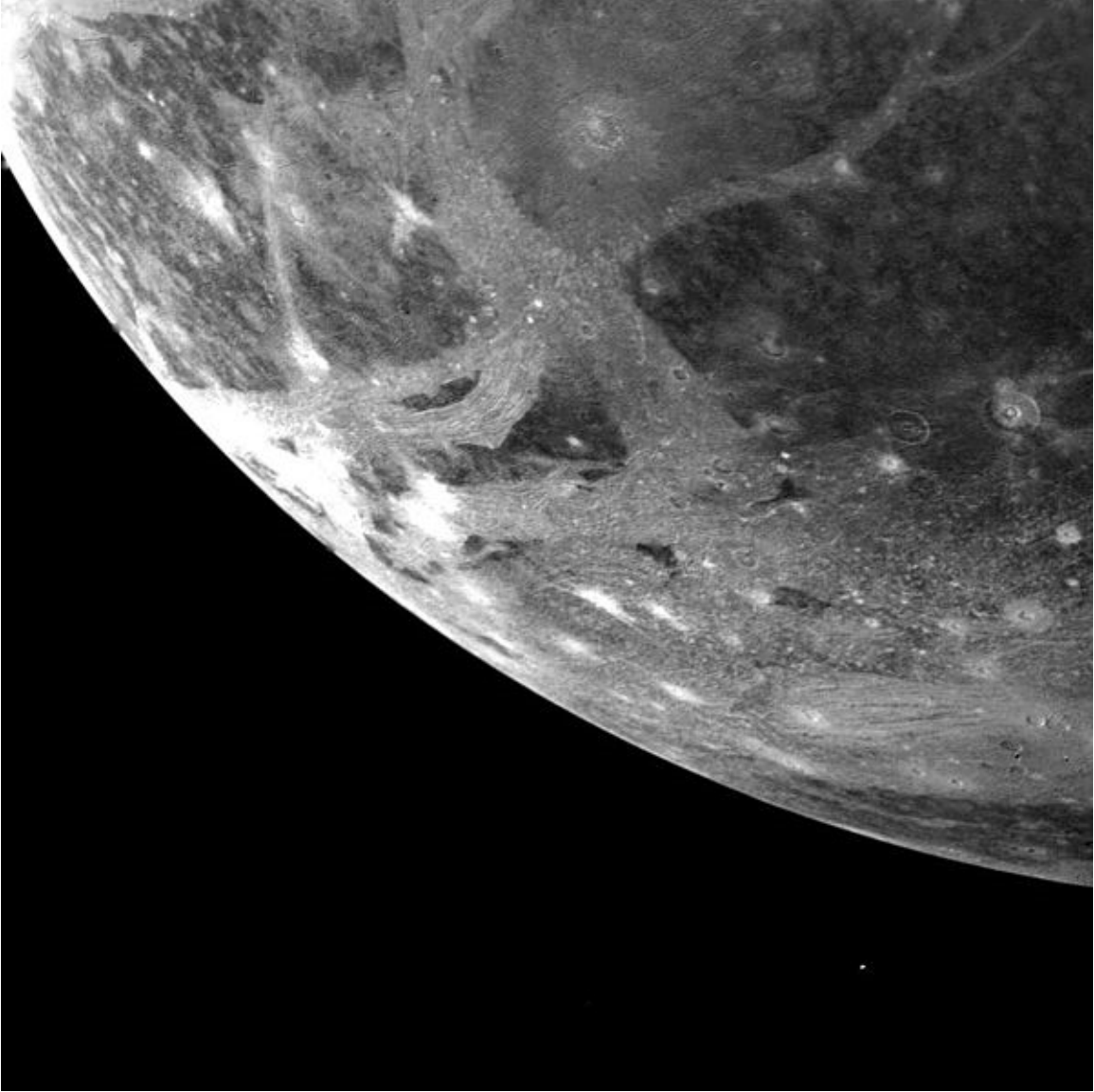


Location and trajectories of Pioneer and Voyager spacecraft, as of July 7, 2007. Note Voyager 2 is farther than Pioneer 11 and only appears closer here due to its -55 degree declination, and that Voyager 1's position is drawn too far away.

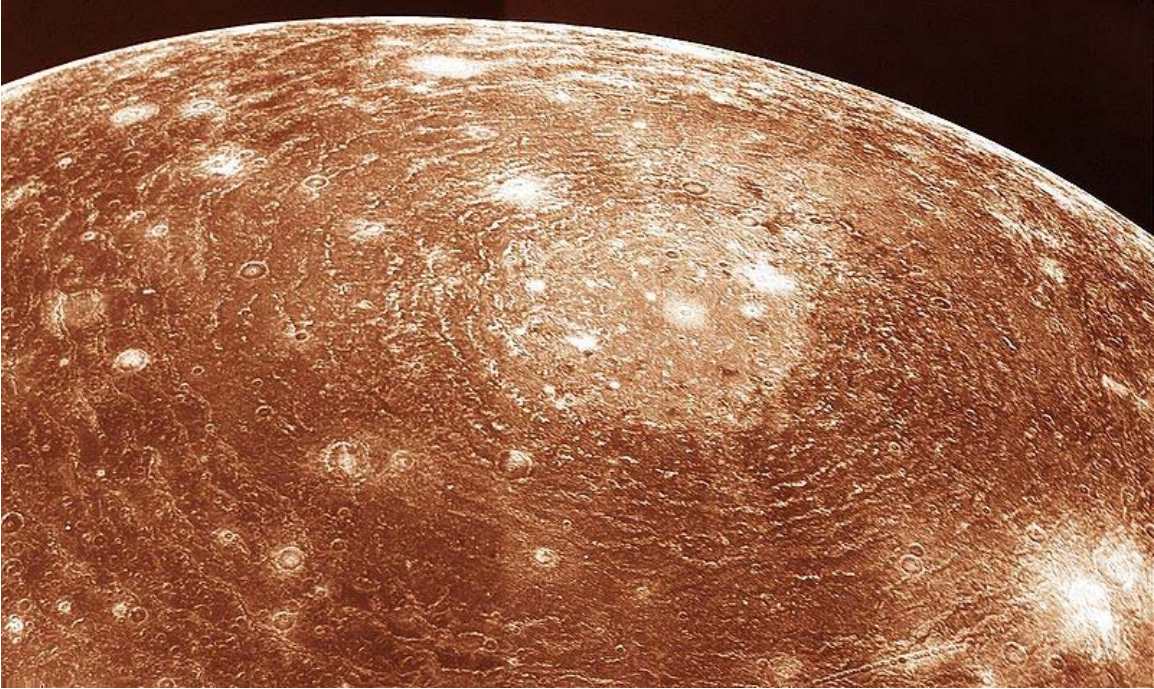
As of **February 17th, 2011**, *Voyager 1* was about 116.205AU (17.242 billion km, or 10.788 billion miles) or about 0.00183 of a light-year from the Sun. Radio signals traveling at the speed of light between Voyager 1 and Earth take 16.14 hours to cross the distance between the two. (To compare, Proxima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



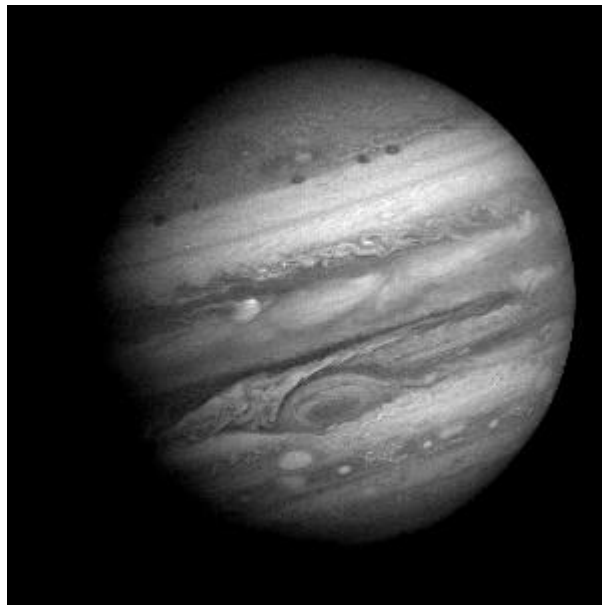
Europa as seen from *Voyager 1* at a distance of 2.8 million km



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



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



Voyager 1 time lapse movie of Jupiter approach

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

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

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

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

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

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

Chapter 4

Voyager 2

Voyager 2



Voyager spacecraft

Operator	NASA / JPL
Mission type	Flyby
Flyby of	Jupiter, Saturn, Uranus, Neptune
Launch date	1977-08-20 14:29:00 UTC (33 years, 5 months, and 30 days ago)
Launch vehicle	Titan IIIE / Centaur
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In Progress (Interstellar mission) (31 years, 7 months, and 10 days elapsed) Jupiter flyby (completed 1979-08-05)

Saturn flyby
(completed 1981-09-25)
Uranus flyby
(completed 1986-02-25)
Neptune flyby
(completed 1989-10-02)

COSPAR ID	1977-076A
Homepage	NASA <i>Voyager</i> website
Mass	721.9 kg (1,592 lb)
Power	420 W (3 RTGs)

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

Mission background

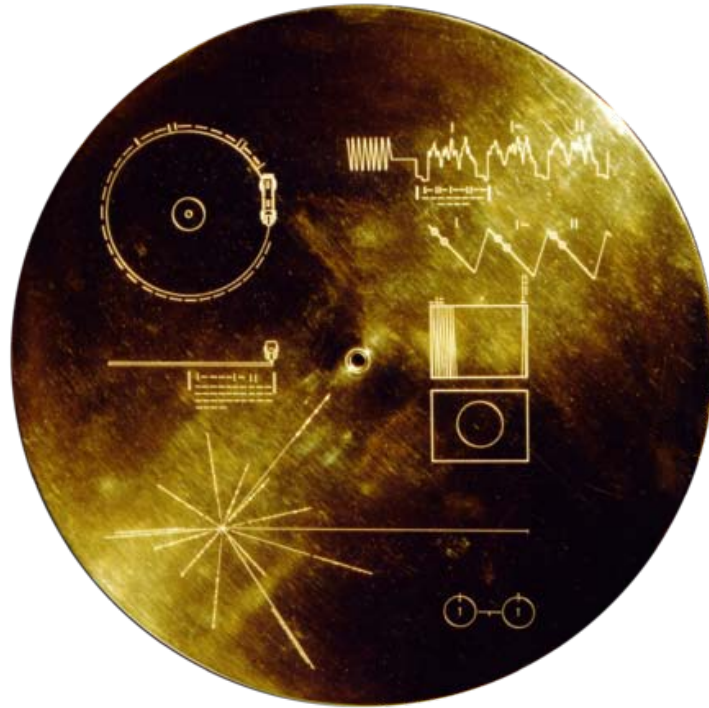
History

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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

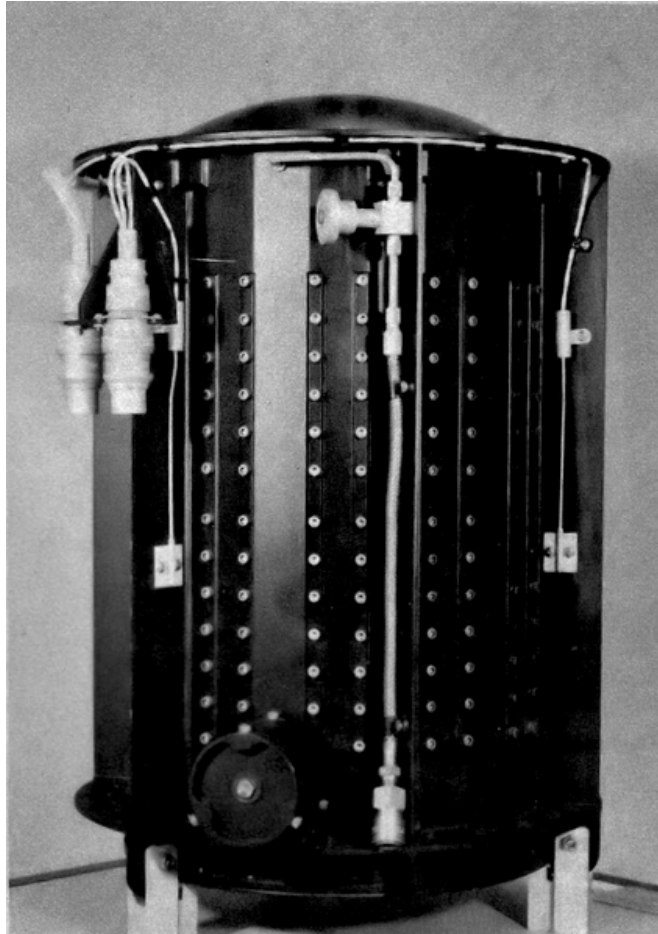
Constructed by the Jet Propulsion Laboratory, *Voyager 2* included 16 hydrazine thrusters, three-axis stabilization, gyroscopes and celestial referencing instruments (sun sensor/Canopus Star Tracker) to maintain pointing of the high-gain antenna toward Earth. Collectively these instruments are part of 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 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.

Scientific instruments

Expand

Instrument Name **Abr.** **Description**
 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
Imaging Science System (disabled)	(ISS)	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

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.

Radio Science System
(disabled) (RSS)

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

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.

Infrared Interferometer Spectrometer
(disabled) (IRIS)

- **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)

Designed to measure atmospheric properties, and to measure radiation.

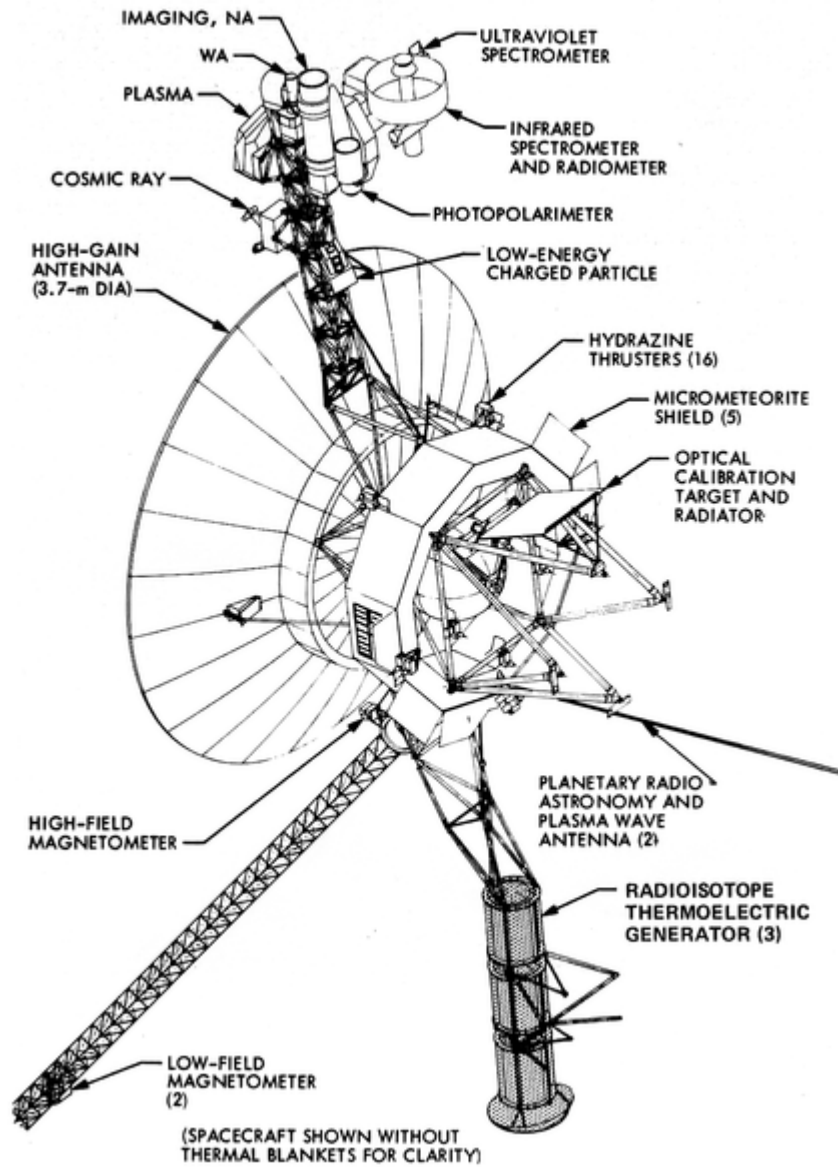
Ultraviolet Spectrometer
(disabled) (UVS)

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

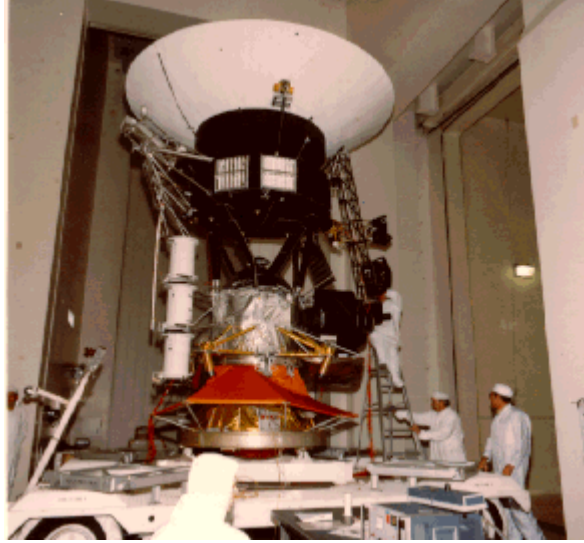
Triaxial Fluxgate (MAG) Designed to investigate the magnetic fields of Jupiter and Saturn, the solar-wind interaction with

Magnetometer (active)		<p>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.</p> <ul style="list-style-type: none"> • Principal investigator: Norman Ness / NASA Goddard Space Flight Center (website) • Data: PDS/PPI data catalog, NSSDC data archive
Plasma Spectrometer (active)	(PLS)	<p>Investigates the macroscopic properties of the plasma ions and measures electrons in the energy range from 5 eV to 1 keV.</p> <ul style="list-style-type: none"> • Principal investigator: John Richardson / MIT (website) • Data: PDS/PPI data catalog, NSSDC data archive
Low Energy Charged Particle Instrument (active)	(LECP)	<p>Measures the differential in energy fluxes and angular distributions of ions, electrons and the differential in energy ion composition.</p> <ul style="list-style-type: none"> • Principal investigator: Stamatios Krimigis / JHU/APL / University of Maryland (JHU/APL website / UMD website / KU website) • Data: UMD data plotting, PDS/PPI data catalog, NSSDC data archive
Cosmic Ray System (active)	(CRS)	<p>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.</p> <ul style="list-style-type: none"> • Principal investigator: Edward Stone / CalTech / NASA Goddard Space Flight Center (website) • Data: NSSDC data archive
Planetary Radio Astronomy Investigation (disabled)	(PRA)	<p>Utilizes a sweep-frequency radio receiver to study the radio-emission signals from Jupiter and Saturn.</p> <ul style="list-style-type: none"> • Principal investigator: James Warwick / University of Colorado • Data: PDS/PPI data catalog
Photopolarimeter System (disabled)	(PPS)	<p>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.</p> <ul style="list-style-type: none"> • Principal investigator: Arthur Lane / JPL (PDS/PRN website) • Data: PDS/PRN data catalog
Plasma Wave System (partially disabled)	(PWS)	<p>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.</p> <ul style="list-style-type: none"> • Principal investigator: Donald Gurnett / University of Iowa (website) • Data: PDS/PPI data catalog, NSSDC data archive

Images of the spacecraft



Voyager spacecraft diagram



Voyager in transport to a solar thermal test chamber



Gold-Plated Record is attached to *Voyager*



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

Timeline of travel

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

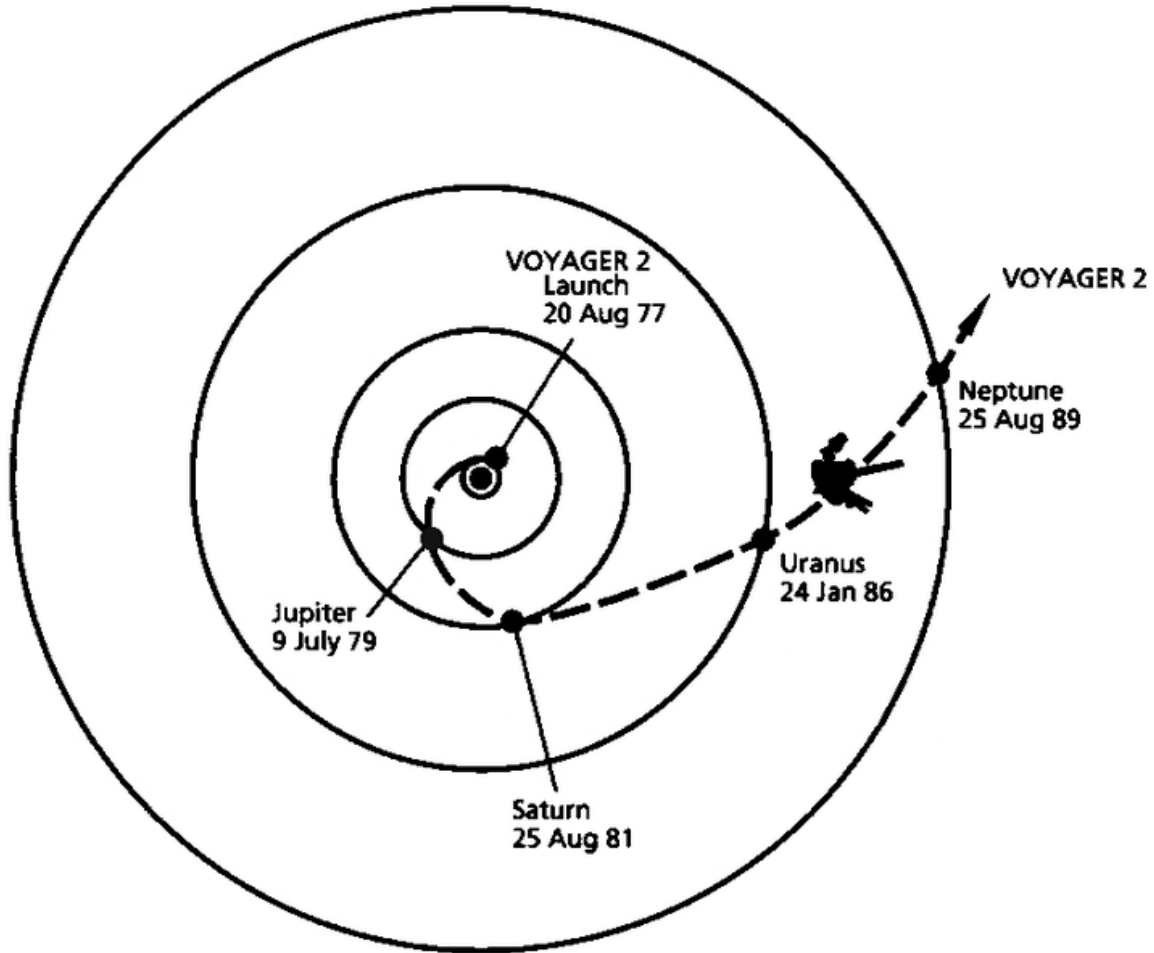
Mission profile

Launch and trajectory

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



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



Trajectory of *Voyager 2* primary mission

Encounter with Jupiter

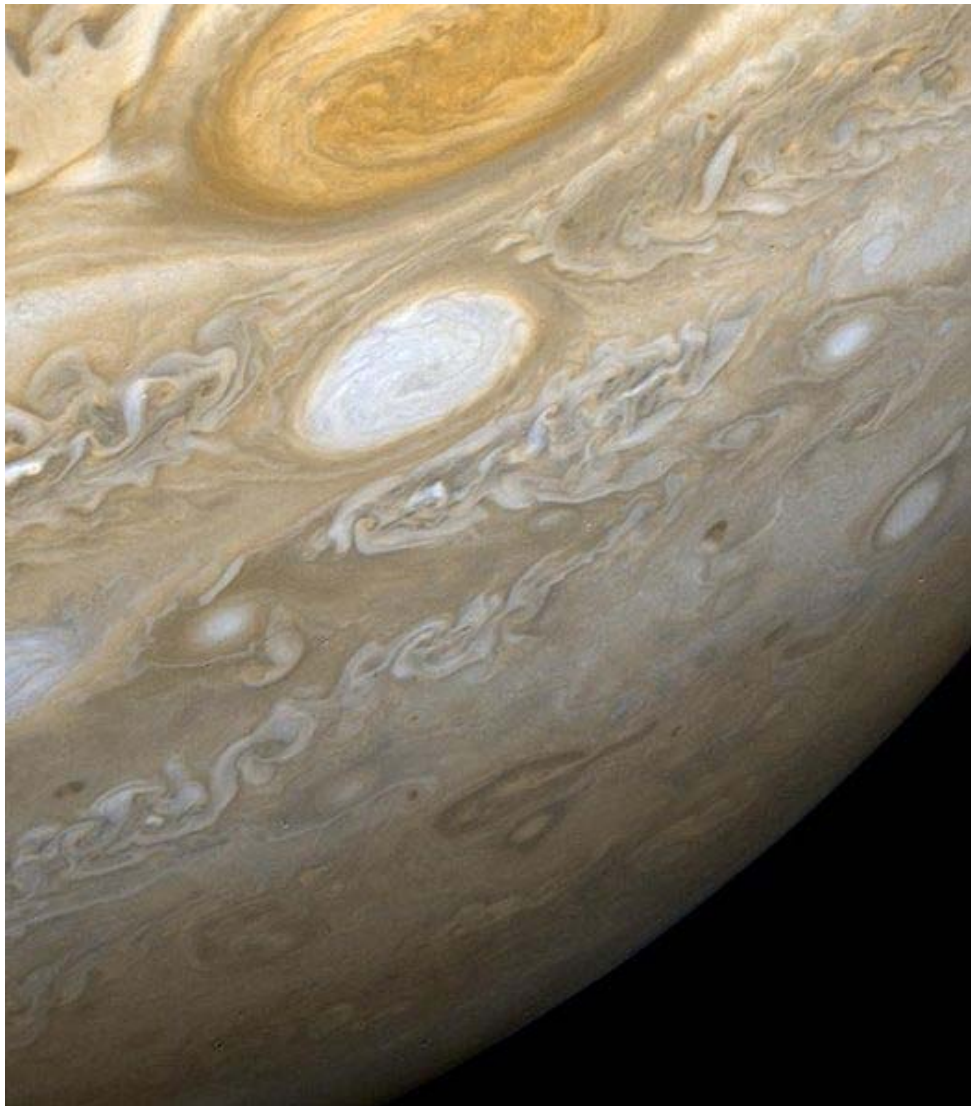
The closest approach to Jupiter occurred on July 9, 1979. It came within 570,000 km (350,000 miles) of the planet's cloud tops. It discovered a few rings around Jupiter, as well as volcanic activity on the moon Io.

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

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

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

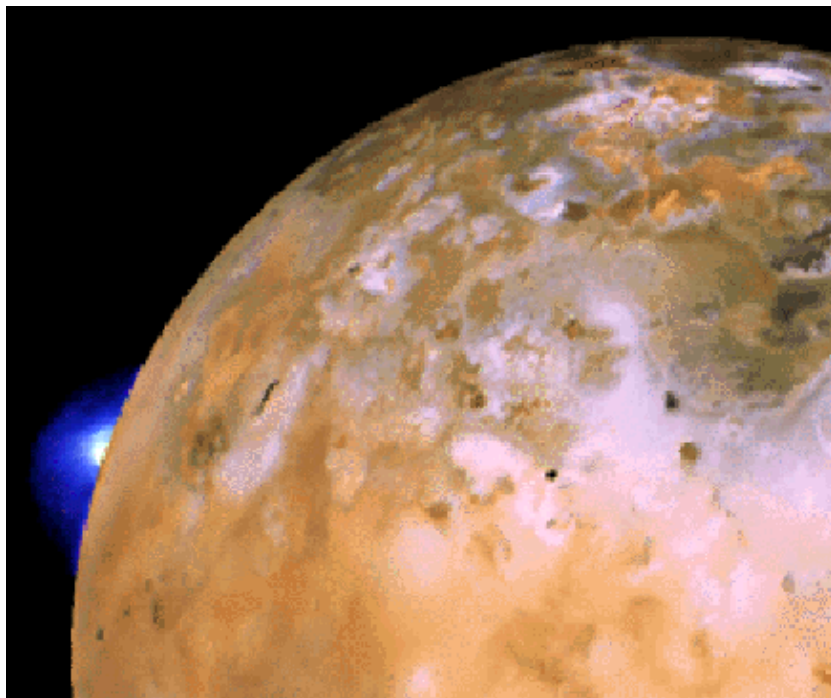
Two new, small satellites, Adrastea and Metis, were found orbiting just outside the ring. A third new satellite, Thebe, was discovered between the orbits of Amalthea and Io.



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



A transit of Io across Jupiter, July 9, 1979



Eruption of a volcano on Io, photographed by Voyager 2



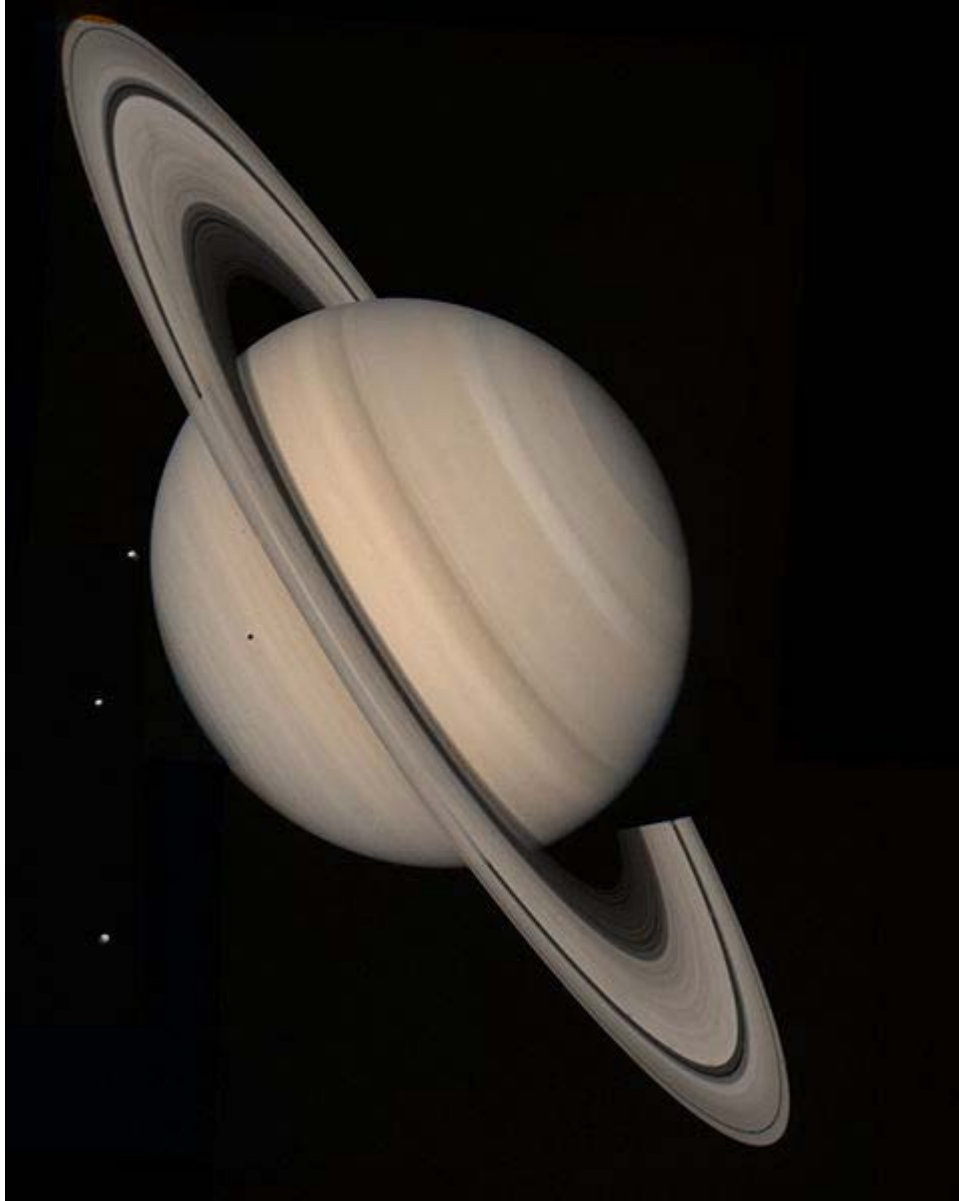
A color mosaic of Europa

Encounter with Saturn

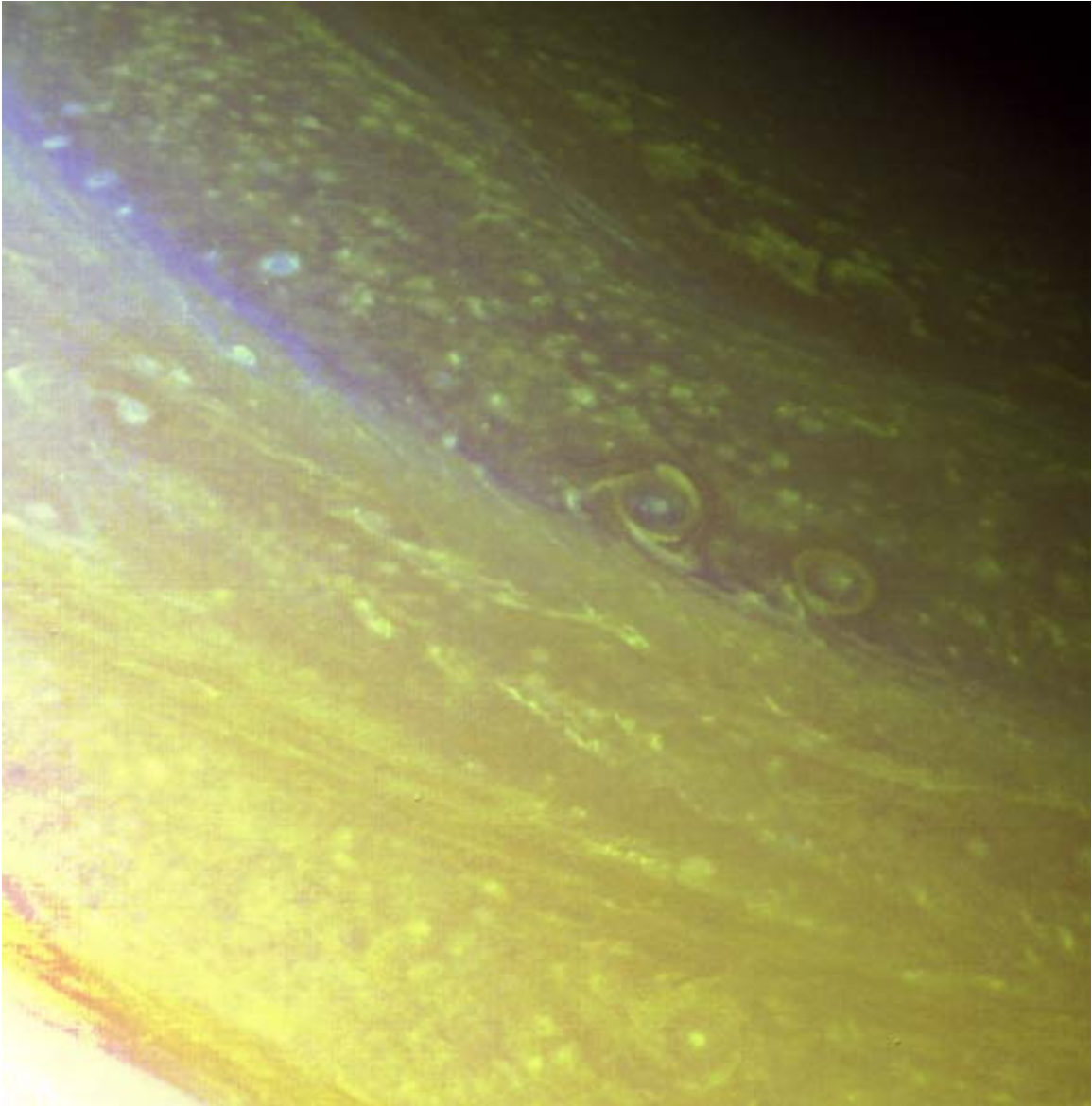
The closest approach to Saturn occurred on August 26, 1981.

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

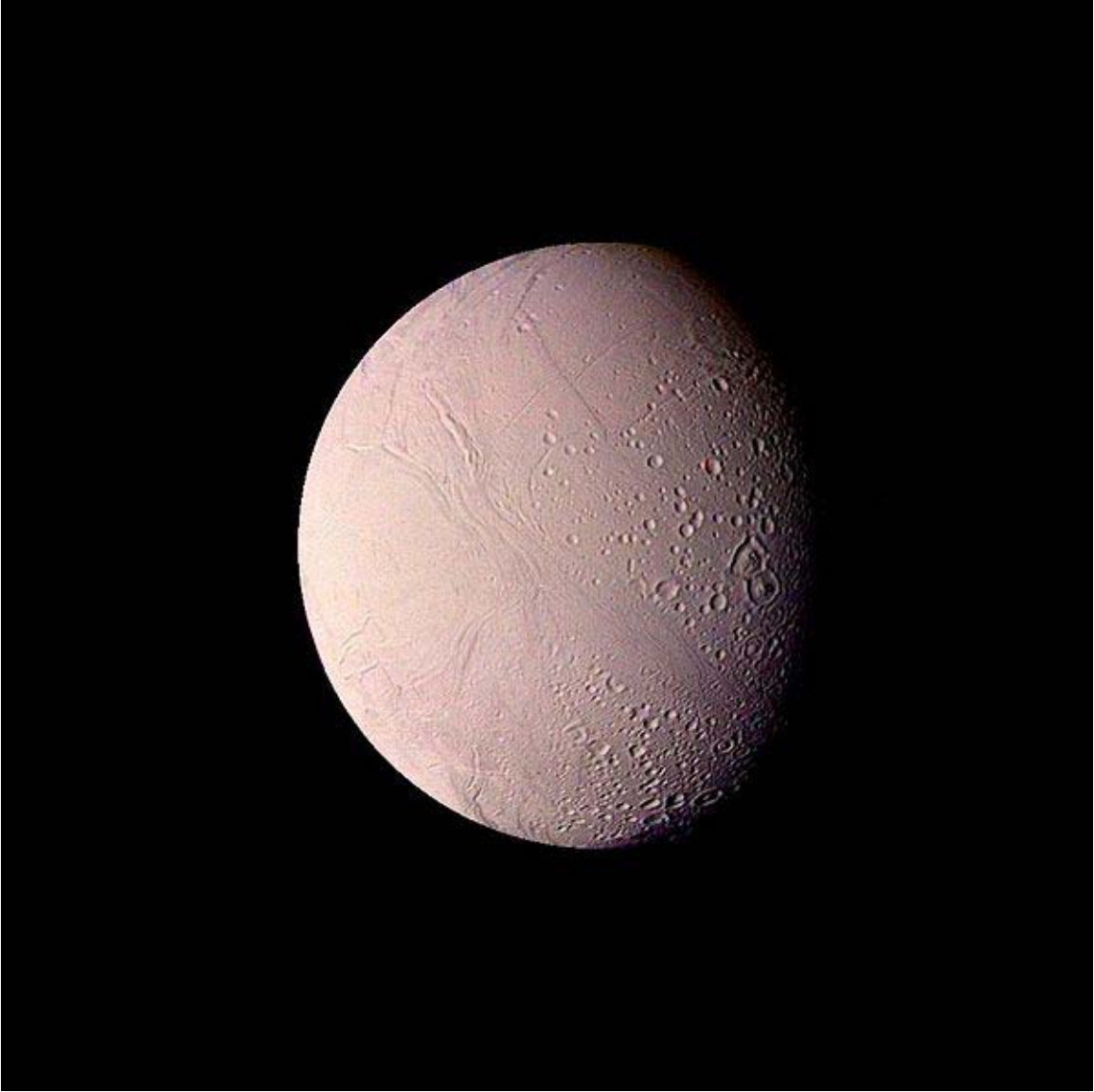
After the fly-by of Saturn, the camera platform of *Voyager 2* locked up briefly, putting plans to officially extend the mission to Uranus and Neptune in jeopardy. Fortunately, the mission's engineers were able to fix the problem (caused by an overuse that temporarily depleted its lubricant), and the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



Voyager 2 Saturn approach view



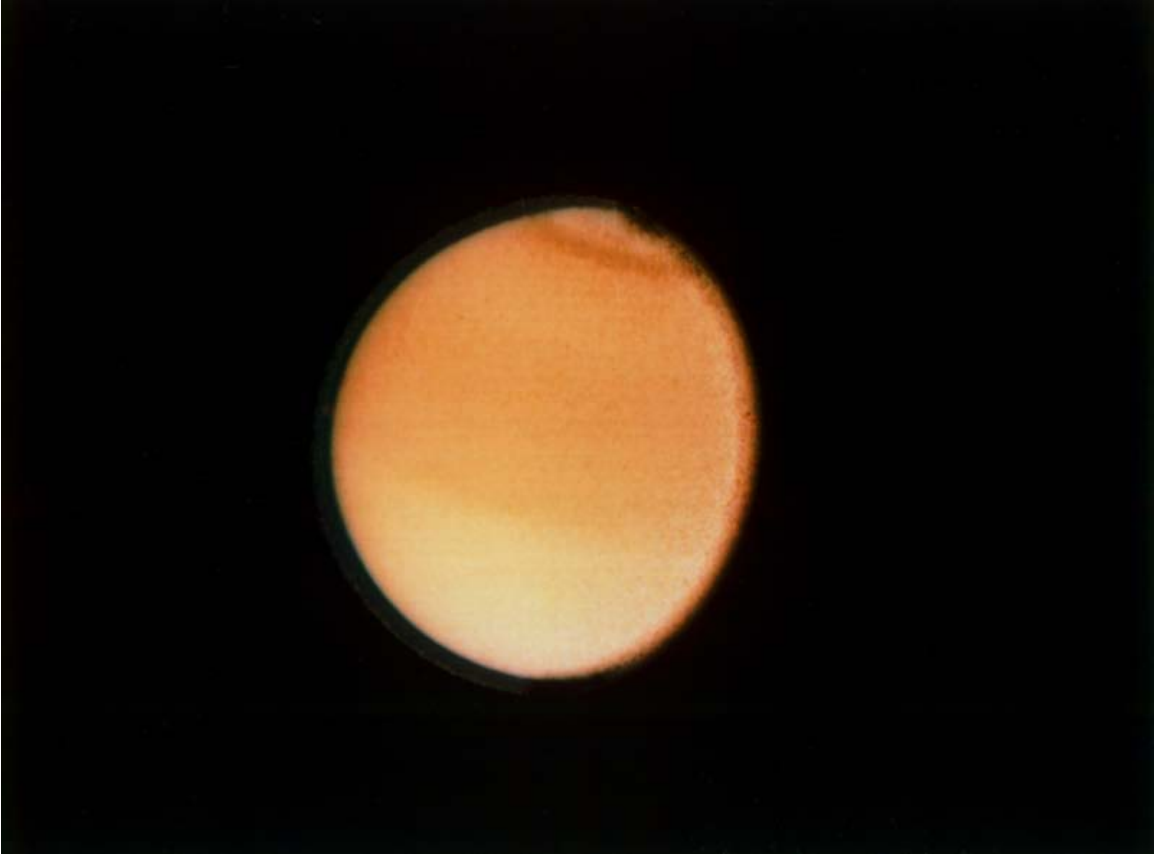
North, polar region of Saturn imaged in orange and UV filters



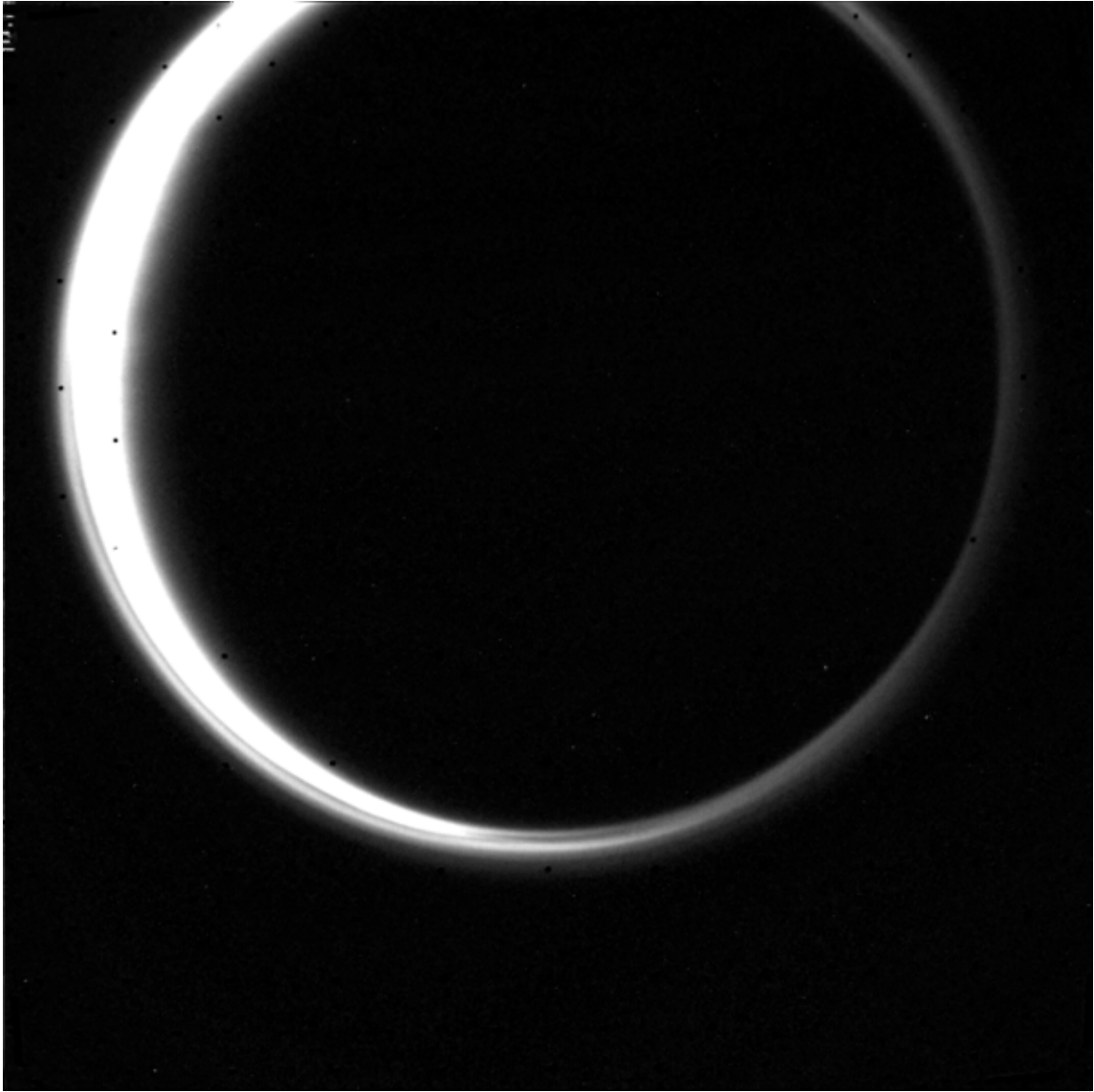
Color image of Enceladus showing terrain of widely varying ages



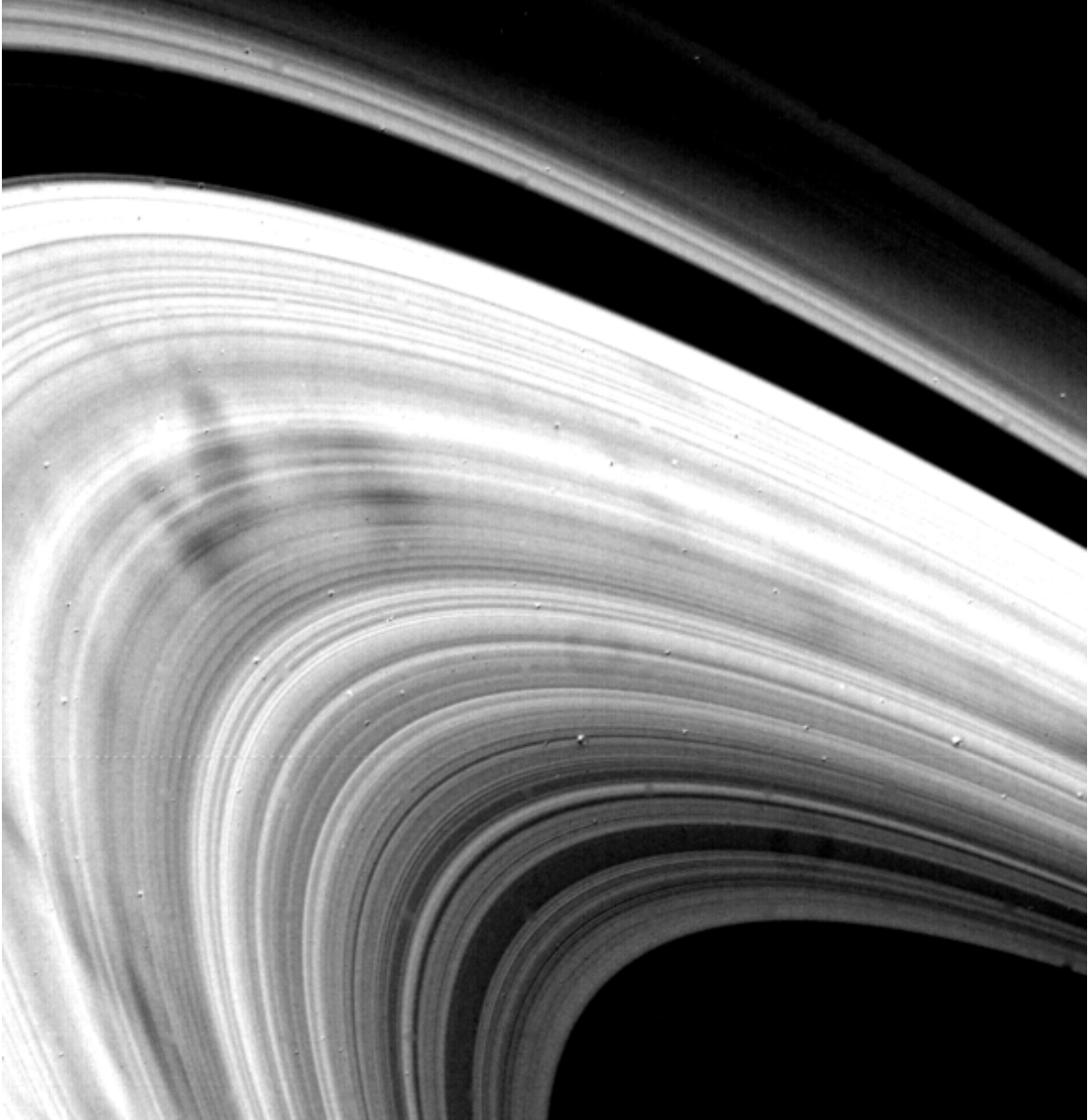
Cratered surface of Tethys at 594,000 km.



Atmosphere of Titan imaged from 2.3 million km.



Titan occultation of the Sun from 0.9 million km.



"Spoke" features observed in the rings of Saturn



Two-toned Iapetus, August 22, 1981

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.

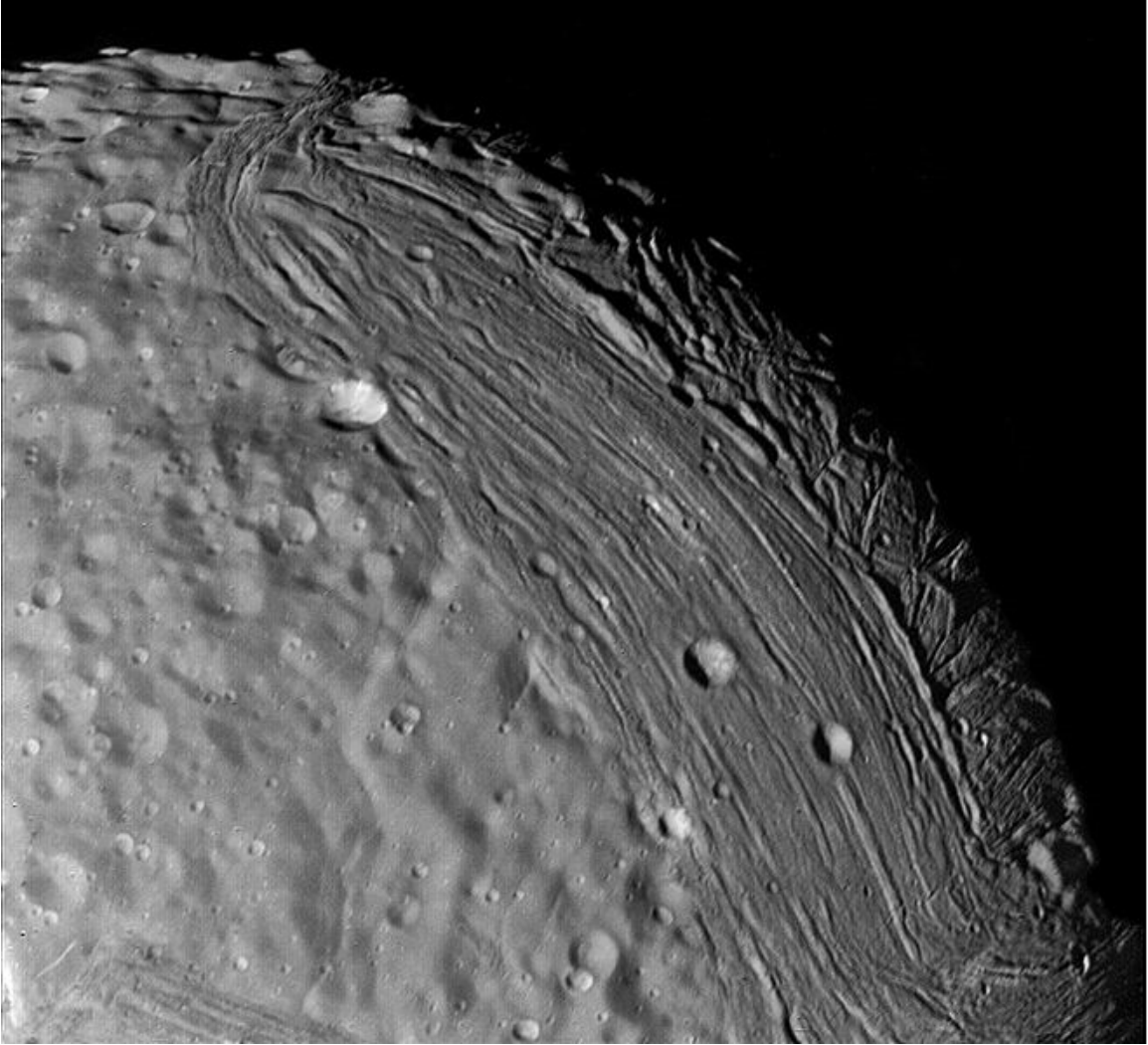
All nine of the previously known Uranian rings were studied by the instruments of *Voyager 2*. These measurements showed that the Uranian rings are distinctly different from those at Jupiter and Saturn. The Uranian ring system might be relatively young, and it did not form at the same time that Uranus 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.



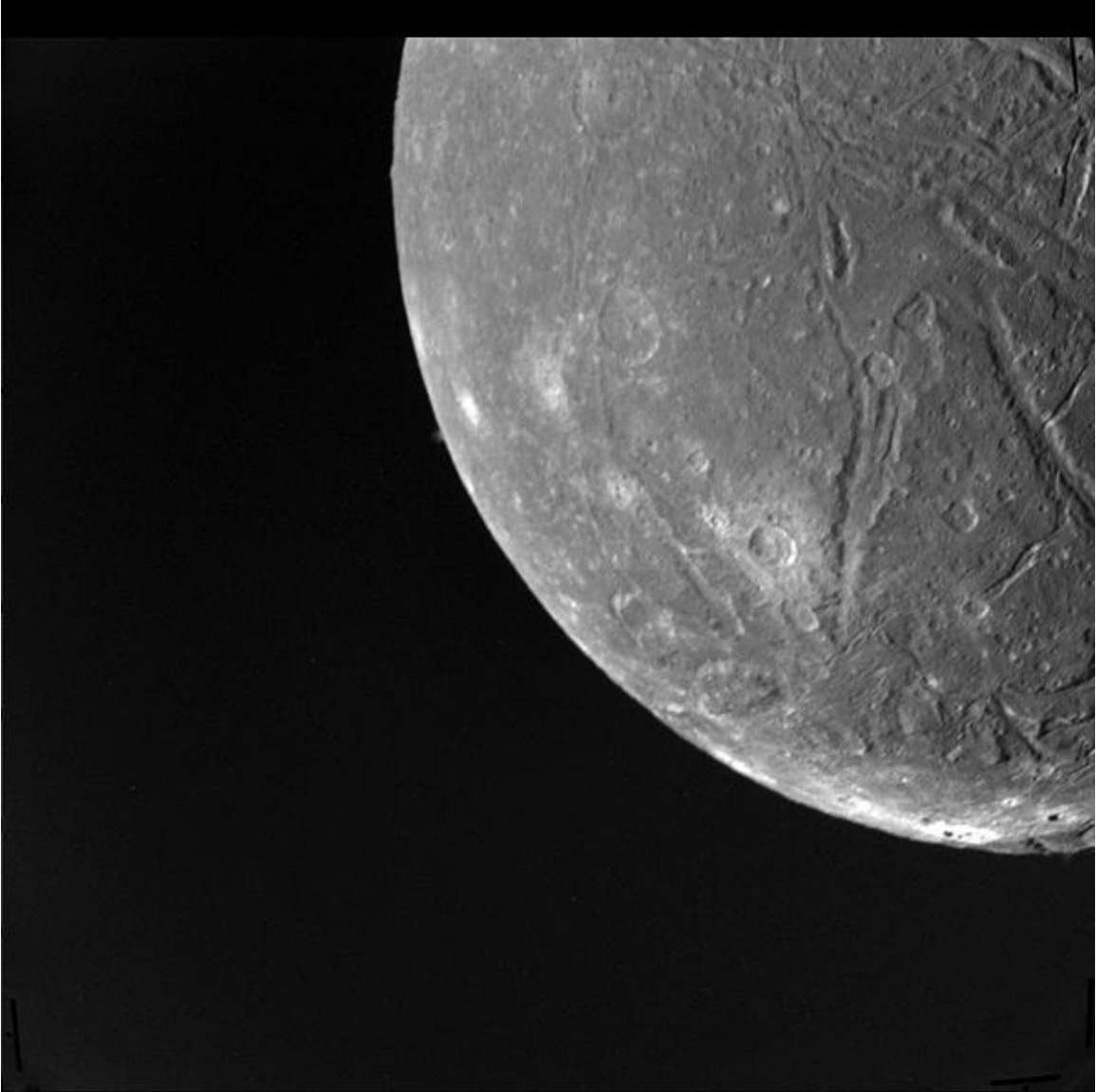
Uranus viewed from 18 million km.



Departing image of crescent Uranus



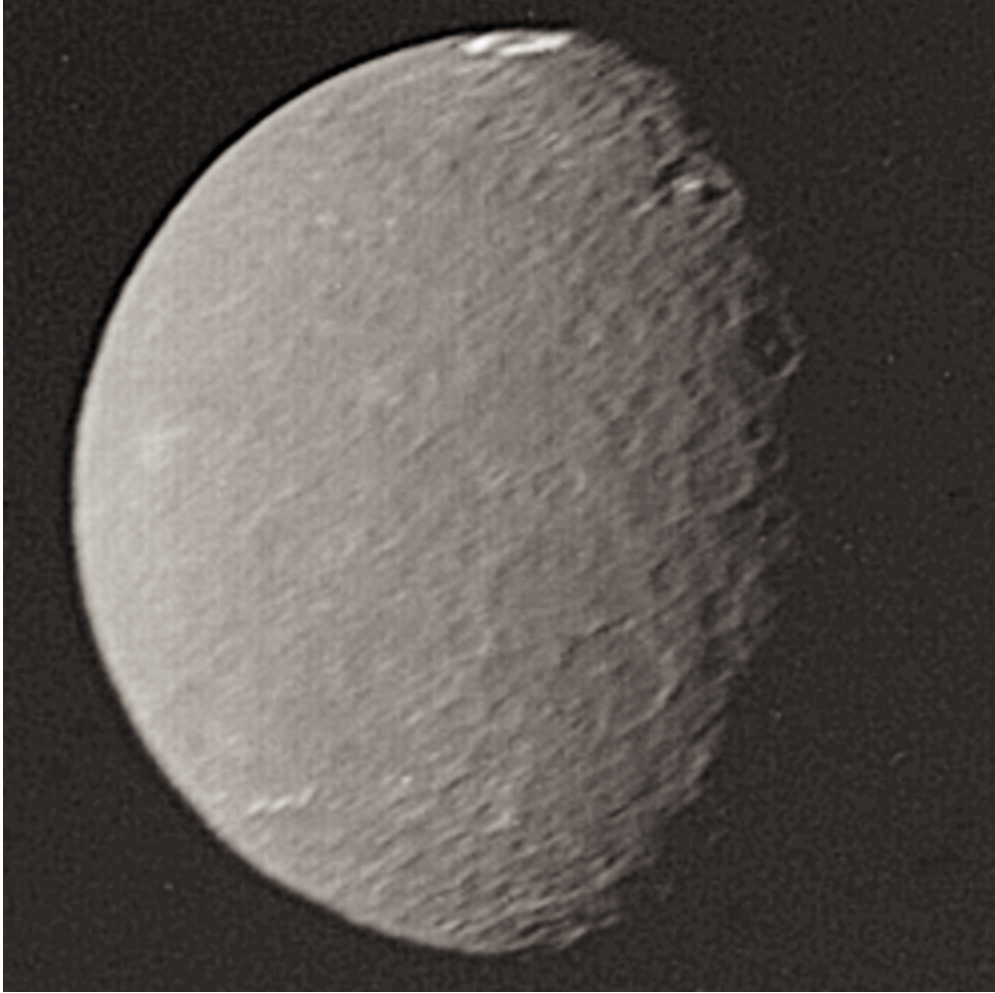
Fractured surface of Miranda



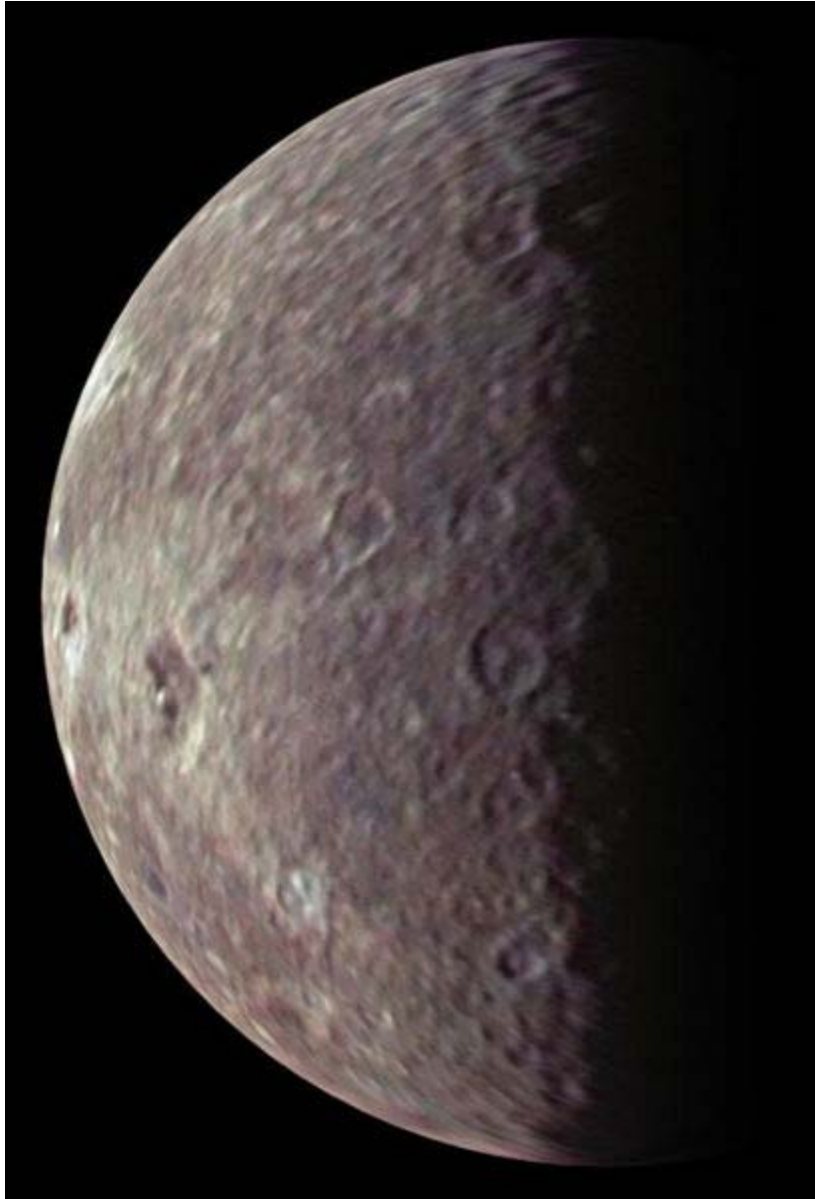
Ariel as imaged from 130,000 km.



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.

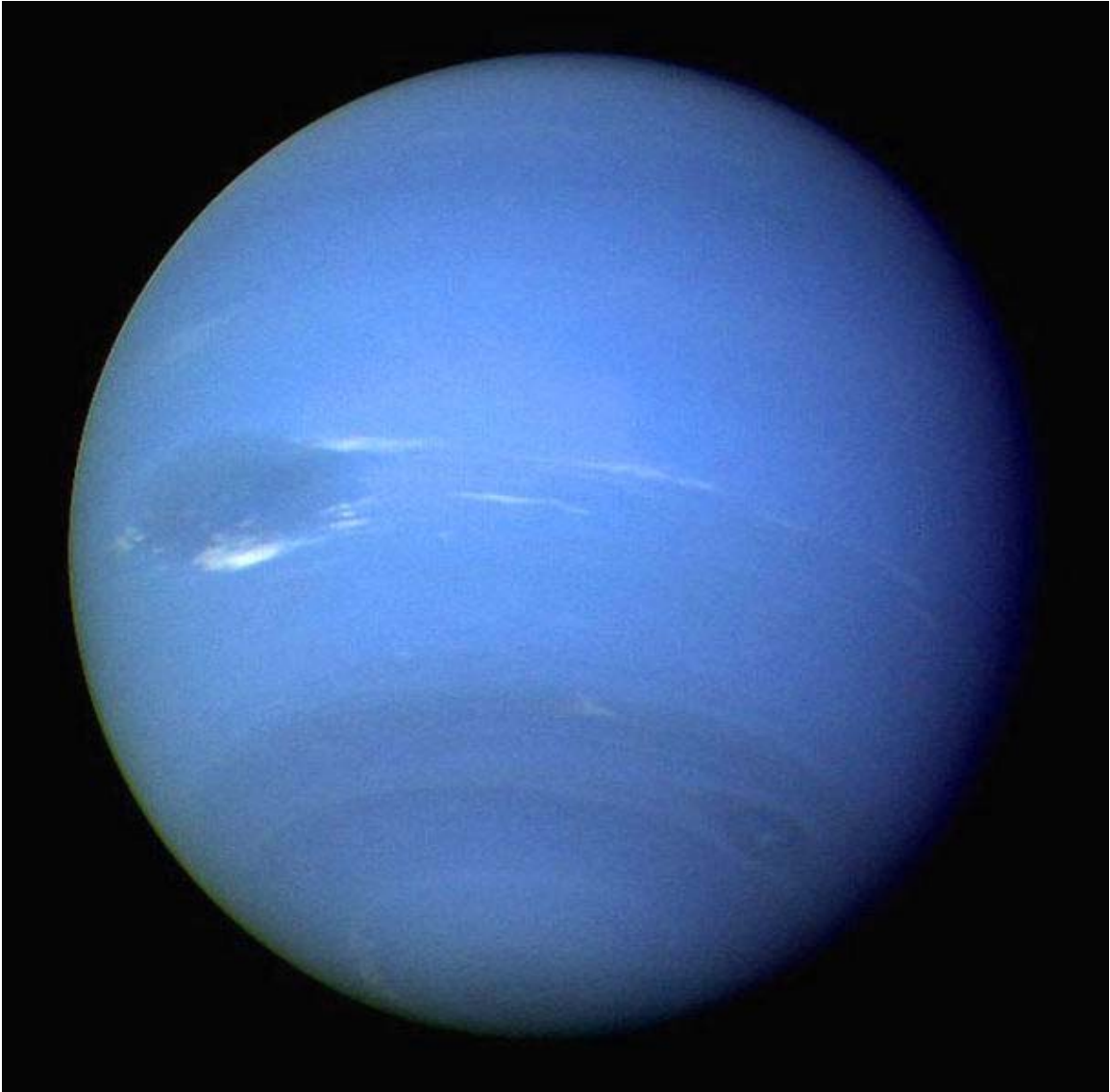
While in the neighborhood of Neptune, *Voyager 2* discovered the "Great Dark Spot", which has since disappeared, according to observations by the Hubble Space Telescope. Originally thought to be a large cloud itself, the "Great Dark Spot" was later hypothesized to be a hole in the visible cloud deck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



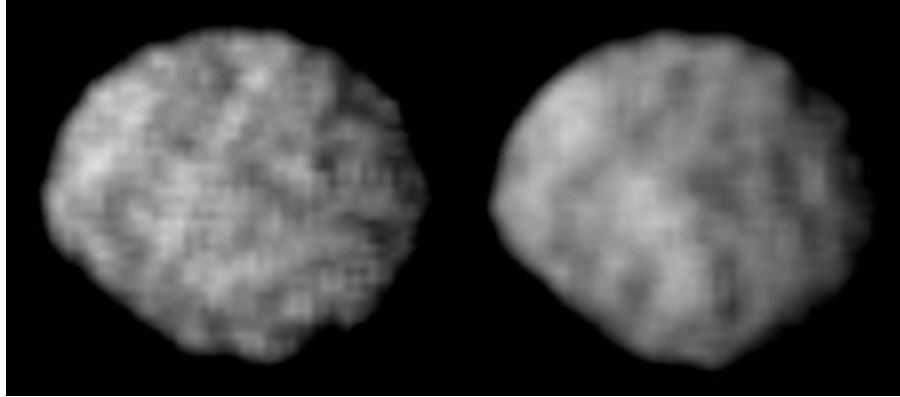
Voyager 2 image of Neptune



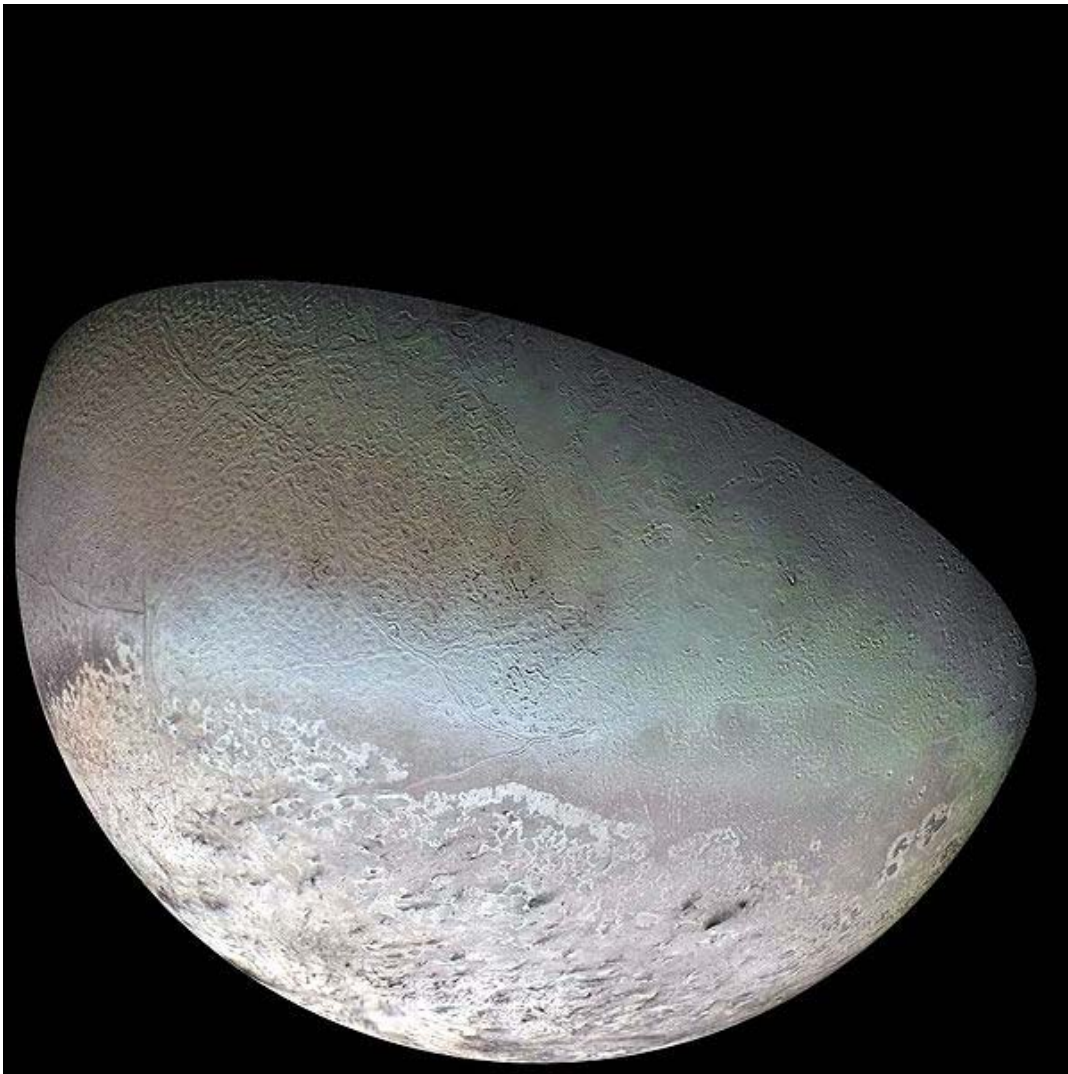
Neptune and Triton three days after *Voyager 2* flyby



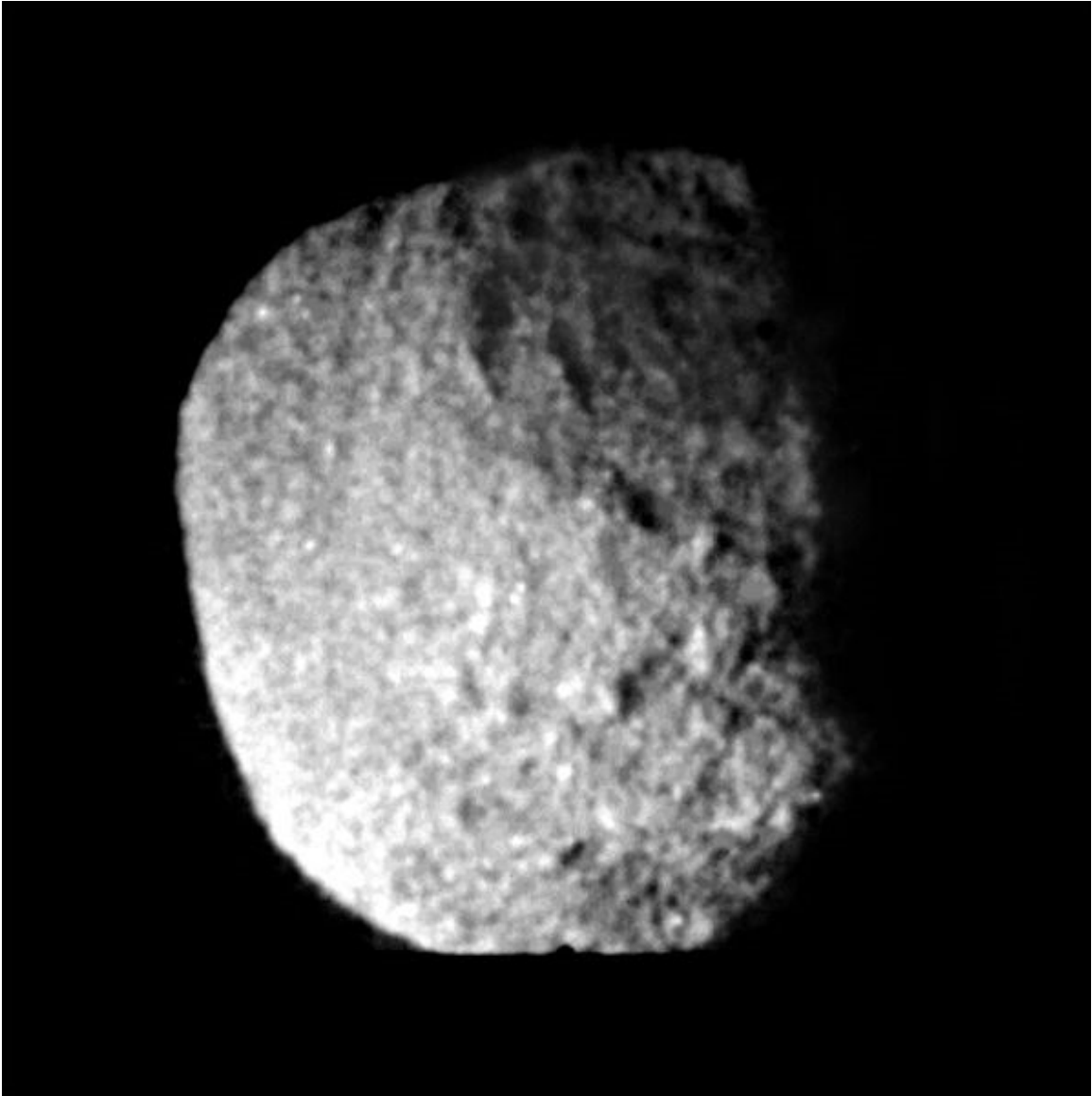
Despina as imaged from *Voyager 2*



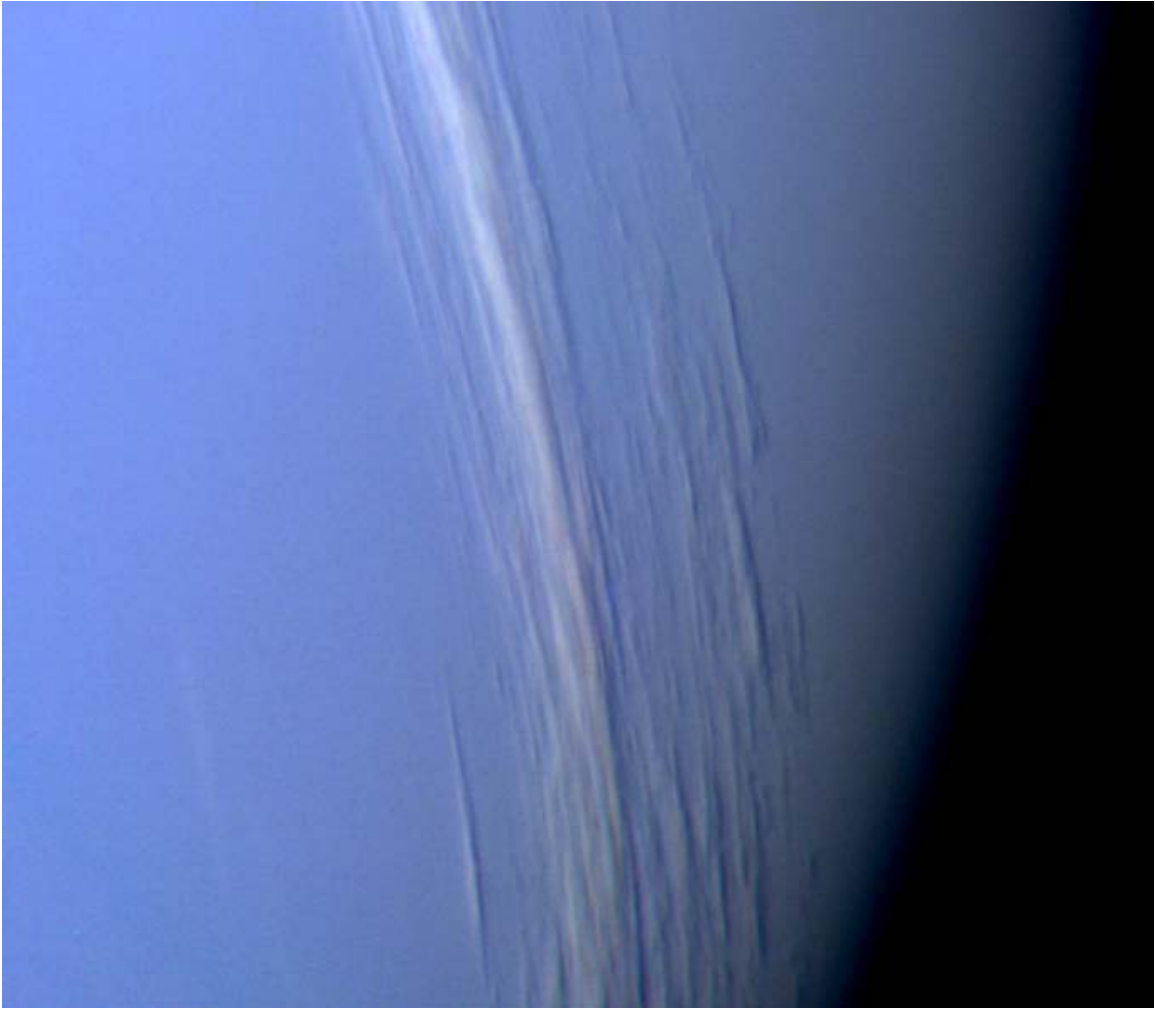
Cratered surface of Larissa



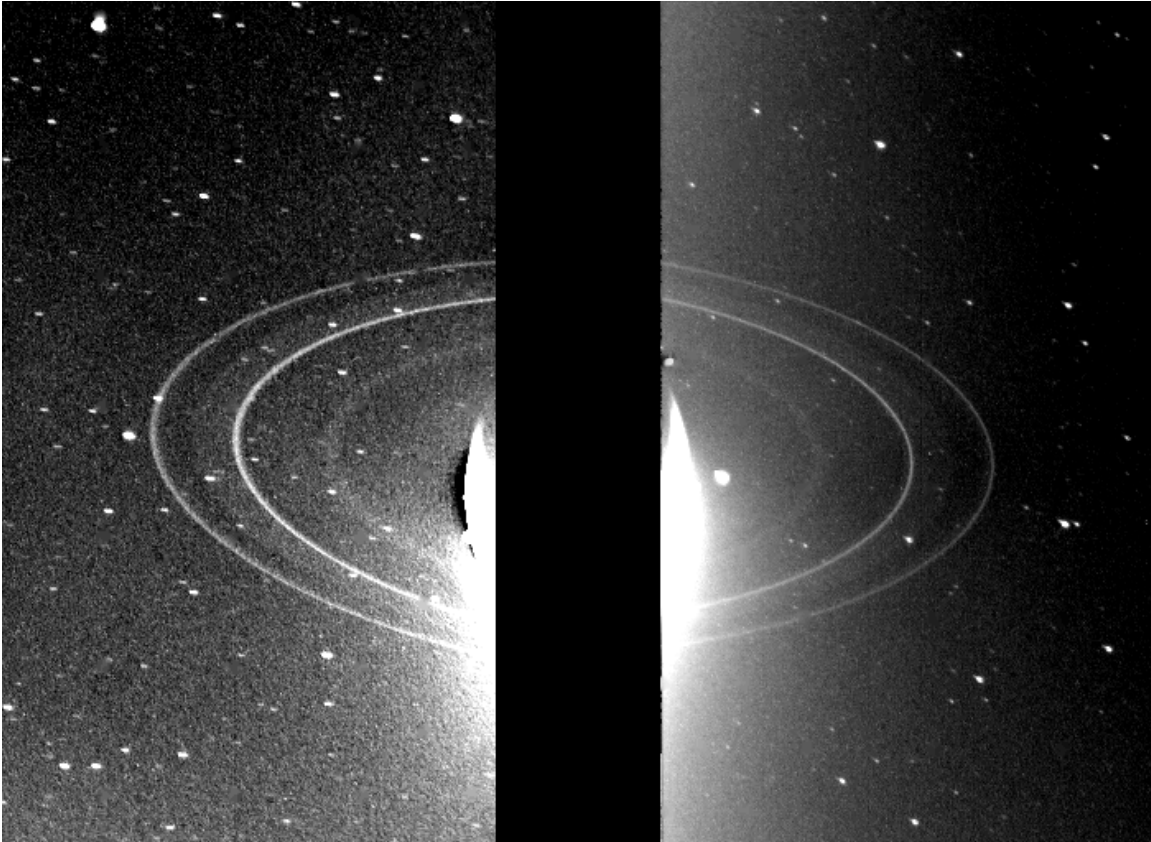
Color mosaic of *Voyager 2* Triton



Dark surface of Proteus



Cirrus clouds imaged above gaseous Neptune



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

Interstellar mission

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

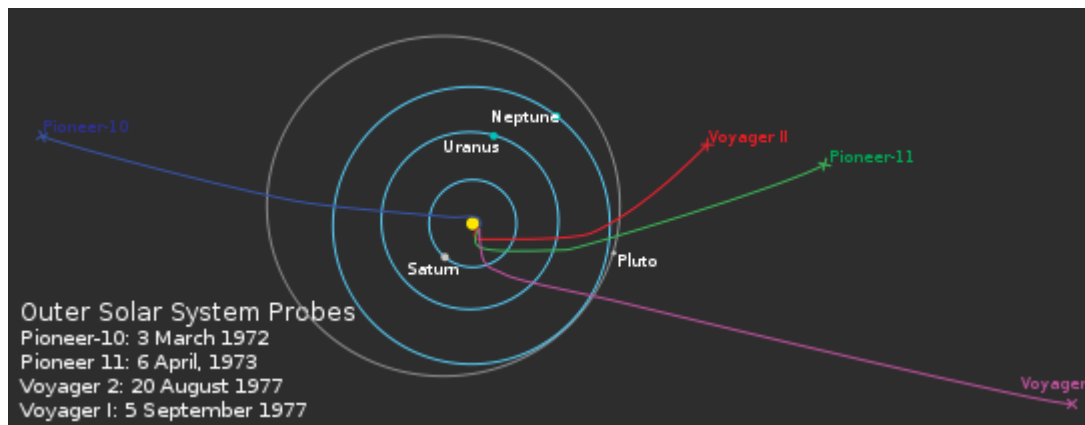
As of April 13, 2010, *Voyager 2* was at a distance of around 91.898 AU (13.747 billion km, 8.542 billion miles or 0.001443 light years) from the Sun, deep in the scattered disc, and traveling outward at roughly 3.264 AU per year. It is more than twice as far from the Sun as Pluto, and far beyond the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

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

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

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

Current status



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

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

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

On November 30, 2006, a telemetered command to *Voyager 2* was incorrectly decoded by its on-board computer—in a random error—as a command to turn on the electrical heaters of the spacecraft's magnetometer. These heaters remained turned on until

December 4, 2006, and during that time, there was a resulting high temperature above 130 °C (266 °F), significantly higher than the magnetometers were designed to endure, and a sensor rotated away from the correct orientation. It has not been possible to fully diagnose and correct for the damage caused to the *Voyager 2's* magnetometer, although efforts to do so are proceeding.

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

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

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

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

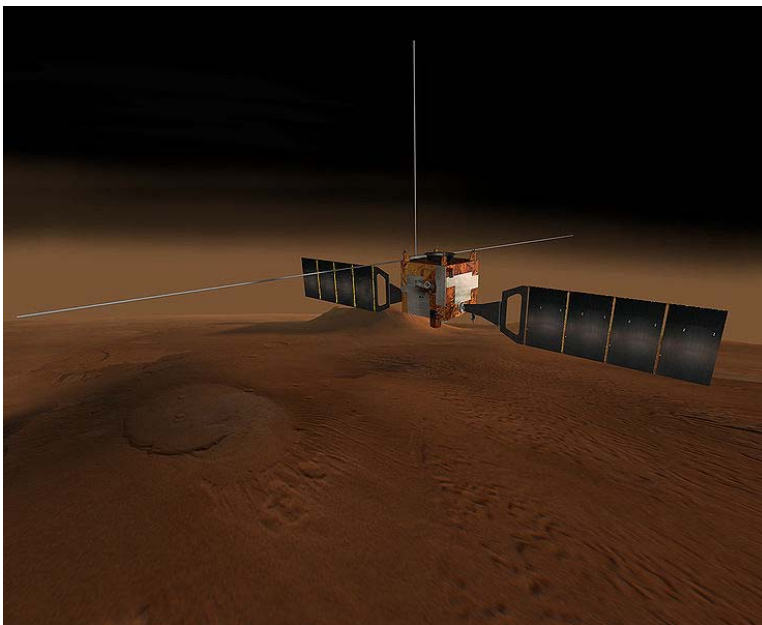
Currently research is being made into making the area of memory with the flipped bit off limits or disallowing its use.

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

Chapter 5

Mars Express

Mars Express



CG image of Mars Express

Operator	ESA
Mission type	Orbiter + Lander
Satellite of	Mars
Orbital insertion date	December 25, 2003
Launch date	June 2, 2003
Launch vehicle	Soyuz-FG/Fregat
COSPAR ID	2003-022A
Mass	1123 (666 + 457 fuel) kg

Power 460 W (Mars)

Orbital elements

Eccentricity 0.943

Inclination 86.3°

Apoapsis 10,107 km

Periapsis 298 km

Orbital period 7.5 hr

Mars Express is a space exploration mission being conducted by the European Space Agency (ESA). The Mars Express mission is exploring the planet Mars, and is the first planetary mission attempted by the agency. "Express" originally referred to the speed and efficiency with which the spacecraft was designed and built. However "Express" also describes the spacecraft's relatively short interplanetary voyage, a result of being launched when the orbits of Earth and Mars brought them closer than they had been in about 60,000 years.

Mars Express consists of two parts, the *Mars Express Orbiter* and the *Beagle 2*, a lander designed to perform exobiology and geochemistry research. Although the lander failed to land safely on the Martian surface, the Orbiter has been successfully performing scientific measurements since early 2004, namely, high-resolution imaging and mineralogical mapping of the surface, radar sounding of the subsurface structure down to the permafrost, precise determination of the atmospheric circulation and composition, and study of the interaction of the atmosphere with the interplanetary medium.

Due to the valuable science return and the highly flexible mission profile, *Mars Express* has been granted four mission extensions, the latest until December 31, 2012.

Some of the instruments on the orbiter, including the camera systems and some spectrometers, reuse designs from the failed launch of the Russian Mars 96 mission in 1996 (European countries had provided much of the instrumentation and financing for that unsuccessful mission). The basic design of Mars Express is based on ESA's Rosetta mission, on which a considerable sum was spent on development. The same design was also used for the *Venus Express* mission in order to increase reliability and reduce development cost and time.

Mission profile and timeline overview

Mission overview

The Mars Express mission is dedicated to the orbital (and originally in-situ) study of the interior, subsurface, surface and atmosphere, and environment of the planet Mars. The

scientific objectives of the Mars Express mission represent an attempt to fulfil in part the lost scientific goals of the Russian Mars-96 mission, complemented by exobiology research with Beagle-2. Mars exploration is crucial for a better understanding of the Earth from the perspective of comparative planetology.

The spacecraft originally carried seven scientific instruments, a small lander, a lander relay and a Visual Monitoring Camera, all designed to contribute to solving the mystery of Mars' missing water. All of the instruments take measurements of the surface, atmosphere and interplanetary media, from the main spacecraft in polar orbit, which will allow it to gradually cover the whole planet.

The overall Mars Express budget excluding the lander is €150 million (roughly US\$185 million).

Spacecraft construction

The prime contractor for the construction of Mars Express Orbiter was EADS Astrium Satellites.

Mission preparation

In the years preceding the launch of a spacecraft numerous teams of experts distributed over the contributing companies and organisations prepared the space and ground segments. Each of these teams focussed on the area of its responsibility and interfacing as required. A major additional requirement raised for the Launch and Early Orbit Phase (LEOP) and all critical operational phases was that it was not enough merely to interface; the teams had to be integrated into one Mission Control Team. All the different experts had to work together in an operational environment and the interaction and interfaces between all elements of the system (software, hardware and human) had to run smoothly for this to happen:

- the flight operations procedures had to be written and validated down to the smallest detail;
- the control system had to be validated;
- system Validation Tests (SVTs) with the satellite had to be performed to demonstrate the correct interfacing of the ground and space segments;
- mission Readiness Test with the Ground Stations had to be performed;
- a Simulations Campaign was run.

Launch

The spacecraft was launched on June 2, 2003 at 23:45 local time (17:45 UT, 1:45 p.m. EDT) from Baikonur Cosmodrome in Kazakhstan, using a Soyuz-FG/Fregat rocket. The Mars Express and Fregat booster were initially put into a 200 km Earth parking orbit, then the Fregat was fired again at 19:14 UT to put the spacecraft into a Mars transfer orbit. The Fregat and Mars Express separated at approximately 19:17 UT. The solar

panels were then deployed and a trajectory correction maneuver was performed on June 4 to aim Mars Express towards Mars and allow the Fregat booster to coast into interplanetary space.

Near earth commissioning phase

The Near Earth Commissioning phase extended from the separation of the spacecraft from the launcher upper stage until the completion of the initial check out of the orbiter and payload. It included the solar array deployment, the initial attitude acquisition, the declamping of the Beagle-2 spin-up mechanism, the injection error correction manoeuvre and the first commissioning of the spacecraft and payload (final commissioning of payload took place after Mars Orbit Insertion). The payload was checked out one instrument at a time. This phase lasted about one month.

The interplanetary cruise phase

This five month phase lasted from the end of the Near Earth Commissioning phase until one month prior to the Mars capture manoeuvre and included trajectory correction manoeuvres and payloads calibration. The payload was mostly switched off during the cruise phase, with the exception of some intermediate check-outs. Although it was originally meant to be a "quiet cruise" phase, it soon became obvious that this "cruise" would be indeed very busy. There were star Tracker problems, a power wiring problem, extra manoeuvres, and on the 28th of October, the spacecraft was hit by one of the largest solar flares ever recorded.

Lander jettison

The Beagle 2 lander was released on December 19 at 8:31 UTC (9:31 CET) on a ballistic cruise towards the surface. It entered Mars' atmosphere on the morning of December 25. Landing was expected to occur at about 02:45 UT on December 25 (9:45 p.m. EST December 24). However, after repeated attempts to contact the lander failed using the Mars Express craft and the NASA Mars Odyssey orbiter, it was declared lost on February 6, 2004, by the Beagle 2 Management Board. On February 11, ESA announced an inquiry would be held into the failure of *Beagle 2*.

Orbit insertion

Mars Express arrived at Mars after a 400 million km journey and course corrections in September and in December 2003.

On December 20 Mars Express fired a short thruster burst to put it into position to orbit the planet. The Mars Express Orbiter then fired its main engine and went into a highly elliptical initial-capture orbit of 250 km × 150,000 km with an inclination of 25 degrees on December 25 at 03:00 UT (10:00 p.m., December 24 EST).

First evaluation of the orbital insertion showed that the orbiter had reached its first milestone at Mars. The orbit was later adjusted by four more main engine firings to the desired 259 km × 11,560 km near-polar (86 degree inclination) orbit with a period of 7.5 hours. Near periapsis the top deck is pointed down towards the Martian surface and near apoapsis the high gain antenna will be pointed towards Earth for uplink and downlink.

After 100 days the apoapsis was lowered to 10,107 km and periapsis raised to 298 km to give an orbital period of 6.7 hours.

MARSIS deployment

On May 4, 2005, *Mars Express* deployed the first of its two 20-metre-long radar booms for its MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) experiment. At first the boom didn't lock fully into place; however, exposing it to sunlight for a few minutes on May 10 fixed the glitch. The second 20 m boom was successfully deployed on June 14. Both 20 m booms were needed to create a 40 m dipole antenna for MARSIS to work; a less crucial 7-meter-long monopole antenna was deployed on June 17. The radar booms were originally scheduled to be deployed in April 2004, but this was delayed out of fear that the deployment could damage the spacecraft through a whiplash effect. Due to the delay it was decided to split the four week commissioning phase in two parts, with two weeks running up to July 4 and another two weeks in December 2005.

The deployment of the booms was a critical and highly complex task requiring effective inter-agency cooperation ESA, NASA, Industry and public Universities.

Nominal science observations began during July 2005.

Operations of the spacecraft

Operations for Mars Express are carried out by a multinational team of engineers from ESA's Operation Centre (ESOC) in Darmstadt. The team began preparations for the mission about 3 to 4 years prior to the actual launch. This involved preparing the ground segment and the operational procedures for the whole mission.

The Mission Control Team is composed of the Flight Control Team, Flight Dynamics Team, Ground Operations Managers, Software Support and Ground Facilities Engineers. All of these are located at ESOC but there are additionally external teams, such as the Project and Industry Support teams, who designed and built the spacecraft. The Flight Control Team consists of:

- The Spacecraft Operations Manager
- Eight Operations Engineers
- Three Mission Planners
- One Spacecraft Analyst
- Five Spacecraft controllers

The team build-up, headed by the Spacecraft Operations Manager, started about 4 years before launch. He was required to recruit a suitable team of engineers that could handle the varying tasks involved in the mission. For Mars Express the engineers came from various other missions. Most of them had been involved with Earth orbiting satellites.

Routine phase: Science return

Since orbit insertion Mars Express has been progressively fulfilling its original scientific goals. Nominally the spacecraft points to Mars while acquiring science and then slews to earth-pointing to downlink the data, although some instruments like Marsis or Radio Science might be operated while spacecraft is earth-pointing.

Mars Express Spacecraft Orbiter and subsystems

Structure

The Mars Express Orbiter is a cube-shaped spacecraft with two solar panel wings extending from opposite sides. The launch mass of 1123 kg includes a main bus with 113 kg of payload, the 60 kg lander, and 457 kg of propellant. The main body is 1.5 m × 1.8 m × 1.4 m in size, with an aluminium honeycomb structure covered by an aluminum skin. The solar panels measure about 12 m tip-to-tip. Two 20 m long wire dipole antennas extend from opposite side faces perpendicular to the solar panels as part of the radar sounder.

Propulsion

The Soyuz/Fregat launcher provided most of the thrust Mars Express needed to reach Mars. The final stage of the Fregat was jettisoned once the probe was safely on a course for Mars. The spacecraft's on-board means of propulsion was used to slow the probe for Mars orbit insertion and subsequently for orbit corrections.

The body is built around the main propulsion system, which consists of a bipropellant 400 N main engine. The two 267-liter propellant tanks have a total capacity of 595 kg. Approximately 370 kg are needed for the nominal mission. Pressurized helium from a 35 liter tank is used to force fuel into the engine. Trajectory corrections will be made using a set of eight 10 N thrusters, one attached to each corner of the spacecraft bus. The spacecraft configuration is optimized for a Soyuz/Fregat, and was fully compatible with a Delta II launch vehicle.

Power

Spacecraft power is provided by the solar panels which contain 11.42 square meters of silicon cells. The originally planned power was to be 660 W at 1.5 AU but a faulty connection has reduced the amount of power available by 30%, to about 460 W. This loss of power is not expected to significantly impact the science return of the mission. Power

is stored in three lithium-ion batteries with a total capacity of 64.8 Ah for use during eclipses. The power is fully regulated at 28 V. During routine phase, the spacecraft's power consumption is in the interval 450 W - 550 W.

Avionics

Attitude control (3-axis stabilization) is achieved using two 3-axis inertial measurement units, a set of two star cameras and two Sun sensors, gyroscopes, accelerometers, and four 12 N·m·s reaction wheels. Pointing accuracy is 0.04 degree with respect to the inertial reference frame and 0.8 degree with respect to the Mars orbital frame. Three on-board systems help Mars Express maintain a very precise pointing accuracy, which is essential to allow the spacecraft to communicate with a 35-metre and 70-metre dish on Earth up to 400 million kilometres away.

Communications

The communications subsystem is composed of 3 antennas: A 1.7 m diameter parabolic dish high-gain antenna and two omnidirectional antennas. The first one provide links (Telecommands uplink and Telemetry downlink) in both X-band (7.1 GHz) and S-band (2.1 GHz) and is used during nominal science phase around Mars. The low gain antennas are used during Launch and early operations to Mars and for eventual contingencies once in orbit. Two Mars lander relay UHF antennas are mounted on the top face for communication with the Beagle 2.

Earth Stations

Although communications with Earth were originally scheduled to take place with the ESA 35-meter wide Ground Station in New Norcia (Australia) New Norcia Station, the mission profile of progressive enhancement and science return flexibility have triggered the use of the newest ESA ESTRACK Ground Station in Cebreros Station, Madrid, Spain.

In addition, further agreements with NASA Deep Space Network have made possible the use of American stations for nominal mission planning, thus increasing complexity but with a clear positive impact in scientific returns.

This inter-agency cooperation has proven effective, flexible and enriching for both sides. On the technical side, it has been made possible (among other reasons) thanks to the adoption of both Agencies of the Standards for Space Communications defined in CCSDS

Thermal

Thermal control is maintained through the use of radiators, multi-layer insulation, and actively controlled heaters. The spacecraft must provide a benign environment for the instruments and on-board equipment. Two instruments, PFS and OMEGA, have infrared

detectors that need to be kept at very low temperatures (about -180 °C). The sensors on the camera (HRSC) also need to be kept cool. But the rest of the instruments and on-board equipment function best at room temperatures (10-20 °C).

The spacecraft is covered in gold-plated aluminium-tin alloy thermal blankets to maintain a temperature of 10-20 °C inside the spacecraft. The instruments that operate at low temperatures to be kept cold are thermally insulated from this relatively high internal temperature, and emit excess heat into space using attached radiators.

Control Unit and Data storage

The spacecraft is run by two Control and Data management Units with 12 gigabits of solid state mass memory for storage of data and housekeeping information for transmission. The on-board computers control all aspects of the spacecraft functioning including switching instruments on and off, assessing the spacecraft orientation in space and issuing commands to change it.

Another key aspect of the Mars Express mission is the Mars Express AI Tool (MEXAR2). The primary purpose of the AI tool is the scheduling of when to download various parts of the collected scientific data back to Earth, a process which used to take ground controllers a significant amount of time. The new AI tool saves operator time, optimizes bandwidth use on the DSN, prevents data loss, and allows better use of the DSN for other space operations as well. The AI decides how to manage the spacecraft's 12 gigabits of storage memory, when the DSN will be available and not be in use by another mission, how to make the best use of the DSN bandwidth allocated to it, and when the spacecraft will be oriented properly to transmit back to Earth.

Lander



The *Beagle 2* lander component of Mars Express, as it would have appeared on the Martian surface.

The *Beagle 2* lander objectives were to characterize the landing site geology, mineralogy, and geochemistry, the physical properties of the atmosphere and surface layers, collect

data on Martian meteorology and climatology, and search for possible signatures of life. However, the landing attempt was unsuccessful and the lander was declared lost. A Commission of Inquiry on *Beagle 2* identified four possible causes, including insufficiently strong airbags and problems with parts of the landing system colliding, but was unable to reach any firm conclusions.

Mars Express instruments

The scientific objectives of the Mars Express Payload are to obtain global high-resolution photo-geology (10 m resolution), mineralogical mapping (100 m resolution) and mapping of the atmospheric composition, study the subsurface structure, the global atmospheric circulation, and the interaction between the atmosphere and the subsurface, and the atmosphere and the interplanetary medium. The total mass budgeted for the science payload is 116 kg.

- **Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA)**(Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) - France - Determines mineral composition of the surface up to 100 m resolution. Is mounted inside pointing out the top face. Instrument mass: 28.6 kg
- **Ultraviolet and Infrared Atmospheric Spectrometer (SPICAM)** - France - Assesses elemental composition of the atmosphere. Is mounted inside pointing out the top face. Instrument mass: 4.7 kg
- **Sub-Surface Sounding Radar Altimeter (MARSIS)** - Italy - A radar altimeter used to assess composition of sub-surface aimed at search for frozen water. Is mounted in the body and is nadir pointing, and also incorporates the two 20 m antennas. Instrument mass: 13.7 kg
- **Planetary Fourier Spectrometer (PFS)** - Italy - Makes observations of atmospheric temperature and pressure (observations suspended in September 2005). Is mounted inside pointing out the top face, currently working. Instrument mass: 30.8 kg
- **Analyzer of Space Plasmas and Energetic Atoms (ASPERA)** - Sweden - Investigates interactions between upper atmosphere and solar wind. Is mounted on the top face. Instrument mass: 7.9 kg
- **High Resolution Stereo Camera (HRSC)**- Germany - Produces color images with up to 2 m resolution. Is mounted inside the spacecraft body, aimed through the top face of the spacecraft, which is nadir pointing during Mars operations. Instrument mass: 20.4 kg
- **Mars Express Lander Communications (MELACOM)** - UK - Allows Mars Express to act as a communication relay for landers on the Martian surface. (Has been tested with Mars Exploration Rovers, and was used to support the landing of NASA's Phoenix mission)
- **Mars Radio Science Experiment (MaRS)** - Uses radio signals to investigate atmosphere, surface, subsurface, gravity and solar corona density during solar conjunctions. It uses the communications subsystem itself.

- A small camera to monitor the lander ejection, VMC.
- More on Payload

Scientific discoveries and important events

For more than 5000 orbits, Mars Express Payload instruments have been nominally and regularly operated. HRSC camera has been consistently mapping the Martian surface with unprecedented resolution and has taken dozens of breath-taking pictures.

2004

- January 23

ESA announced the discovery of water ice in the South Polar ice cap, using data taken on January 18 with the OMEGA instrument.

- January 28

Mars Express Orbiter reaches final science orbit around Mars.

- March 17

Orbiter detects polar ice caps that contain 85% highly carbon dioxide (CO₂) ice and 15% water ice.

- March 30

A press release announces that the orbiter has detected methane in the Martian atmosphere. Although the amount is small, about 10 parts in a thousand million, it has excited scientists ask about its source. Since methane is removed from the Martian "air" very fast, there needs to be a current source that releases fresh methane still today. Because one of the possible sources could be microbial life, it is planned to verify the reliability of this data and especially watch for difference in the concentration in various places on Mars. It is hoped that the source of this gas can be discovered by finding its location of release.

- April 28

ESA announced that the deployment of the boom carrying the radar based MARSIS antenna was delayed. It described concerns with the motion of the boom during deployment, which can cause the spacecraft to be struck by elements of it. Further investigations are planned to make sure that this will not happen.

- July 15

Scientists working with the PFS instrument announced that they tentatively discovered the spectral features of the compound ammonia in the Martian atmosphere. Just like methane discovered earlier (see above), ammonia breaks down rapidly in Mars' atmosphere and needs to be constantly replenished. This points towards the existence of active life or geological activity; two contending phenomena whose presence so far have remained undetected.

2005

- In 2005, ESA scientists reported that the OMEGA (Visible and Infrared Mineralogical Mapping Spectrometer)(Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) instrument data indicates the presence of hydrated sulphates, silicates and various rock-forming minerals.

- February 8

The delayed deployment of the MARSIS antenna has been given a green light by ESA. It is planned to take place in early May 2005.

- May 5

The first boom of the MARSIS antenna was successfully deployed. At first, there was no indication of any problems, but later it was discovered that one segment of the boom did not lock. The deployment of the second boom was delayed to allow for further analysis of the problem.

- May 11

Using the Sun's heat to expand the segments of the MARSIS antenna, the last segment locked in successfully.

- June 14

The second boom was deployed, and on June 16 ESA announced it was a success.

- June 22

ESA announces that MARSIS is fully operational and will soon begin acquiring data. This comes after the deployment of the third boom on June 17, and a successful transmission test on June 19.

2006

- September 21

ESA's Mars Express High Resolution Stereo Camera (HRSC) has obtained images of the Cydonia region, the location of the famous "Face on Mars". The massif became famous in a photo taken in 1976 by the American Viking 1 Orbiter. The image recorded with a ground resolution of approximately 13.7 metres per pixel.

- September 26

The Mars Express spacecraft has emerged from an unusually demanding eclipse season introducing a special, ultra-low-power mode nicknamed 'Sumo' - an innovative configuration aimed at saving the power necessary to ensure spacecraft survival.

This mode was developed through tight teamwork between ESOC mission controllers, principal investigators, industry and mission management.

- October

In October 2006 the Mars Express spacecraft has encountered a superior solar conjunction (alignment of Earth-Sun-Mars Express). The angle Sun-Earth-MEX reached a minimum on 23-Oct at 0.39 deg. at a distance of 2.66 AU. Operational measures were undertaken to minimize the impact of the link degradation, since the higher density of electrons in the solar plasma heavily impacts the radio frequency signal. More on

- December

Following the loss of NASA JPL Mars spacecraft Mars Global Surveyor (MGS), Mars Express team was requested to perform actions in the hopes of visually identifying the American spacecraft. Based on last ephemeris of MGS provided by JPL, the on-board high definition HRSC camera swept a region of the MGS orbit. Two attempts were made to find the craft, both unsuccessful.

2007

- January

First agreements with NASA-SPL undertaken for the support of Mars Express on the landing of the American lander Phoenix in May 2008

- February

The small camera VMC (used only once to monitor the lander ejection) has been recommissioned and first steps had been taken to offer students the possibility to participate in a campaign "Command Mars Express Spacecraft and take your own picture of Mars".

- February 23

As result of the important science return, the Science Program Committee (SPC) has granted a mission extension until May 2009 to Mars Express.

- June 28

The High Resolution Stereo Camera (HRSC) has produced dramatic images of key tectonic features in Aeolis Mensae.

2008

The Mars Express Team was the winner of the Sir Arthur Clarke Award for Best Team Achievement.

2009

- February 4

The ESA's Science Programme Committee has extended the operations of Mars Express until December 31, 2009.

- October 7

ESA's Science Programme Committee has approved the extension of mission operations for Mars Express until 31 December 2012.

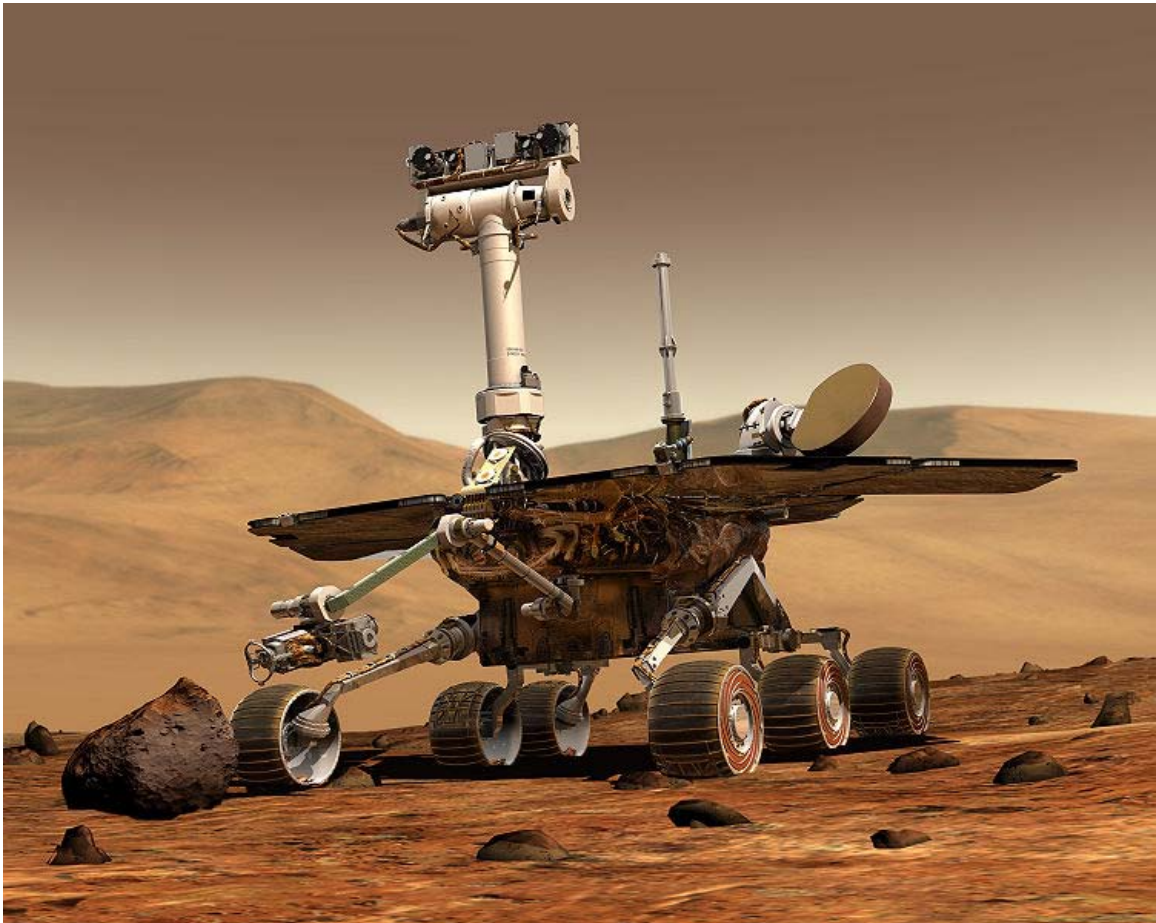
2010

- March 5

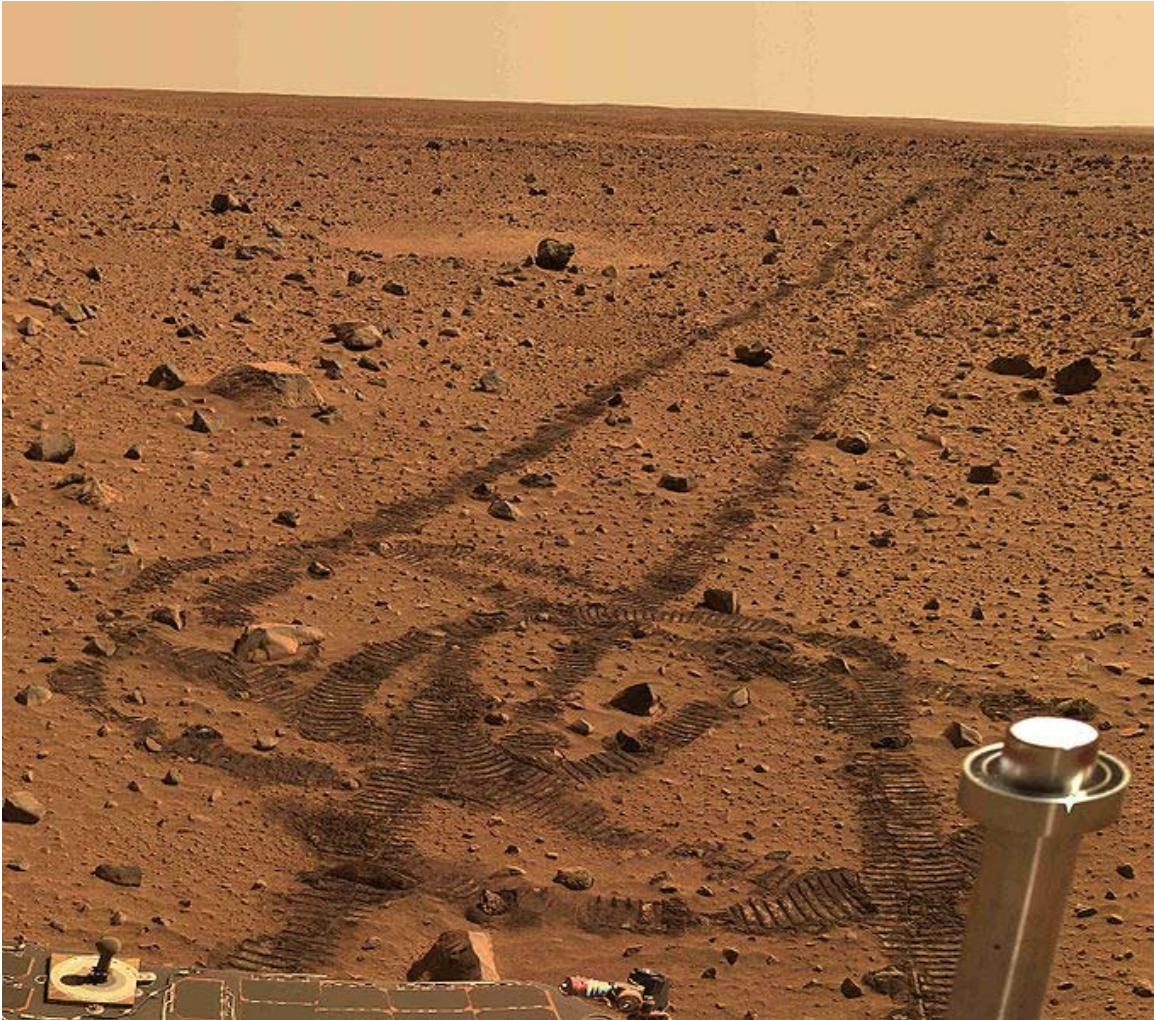
Flyby of Phobos to try to measure Phobos' gravity

Chapter 6

Mars Exploration Rover



Artist's conception of rover on Mars



Part of a panorama taken by the Spirit rover in 2004

NASA's **Mars Exploration Rover Mission (MER)** is an ongoing robotic space mission involving two rovers, *Spirit and Opportunity*, exploring the planet Mars. It began in 2003 with the sending of the two rovers — MER-A *Spirit* and MER-B *Opportunity* — to explore the Martian surface and geology.

The mission's scientific objective was to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The mission is part of NASA's Mars Exploration Program, which includes three previous successful landers: the two Viking program landers in 1976 and Mars Pathfinder probe in 1997.

The total cost of building, launching, landing and operating the rovers on the surface for the initial 90-Martian-day (sol) primary mission was US\$820 million. Since the rovers have continued to function beyond their initial 90 sol primary mission, they have each received five mission extensions. The fifth mission extension was granted in October 2007, and runs to the end of 2009. The total cost of the first four mission extensions was \$104 million, and the fifth mission extension is expected to cost at least \$20 million.

In July 2007, during the fourth mission extension, Martian dust storms blocked sunlight to the rovers and threatened the ability of the craft to gather energy through their solar panels, causing engineers to fear that one or both of them might be permanently disabled. However, the dust storms lifted, allowing them to resume operations.

On May 1, 2009, during its fifth mission extension, *Spirit* became stuck in soft soil on Mars. After nearly nine months of attempts to get the rover back on track, including using test rovers on Earth, NASA announced on January 26, 2010 that *Spirit* was being retasked as a stationary science platform. This mode will enable *Spirit* to assist scientists in ways that a mobile platform could not, such as detecting "wobbles" in the planet's rotation that would indicate a liquid core.

In recognition of the vast amount of scientific information amassed by both rovers, two asteroids have been named in their honor: 37452 Spirit and 39382 Opportunity. The mission is managed for NASA by the Jet Propulsion Laboratory, which designed, built, and is operating the rovers.

Objectives

The scientific objectives of the Mars Exploration Rover mission are to:

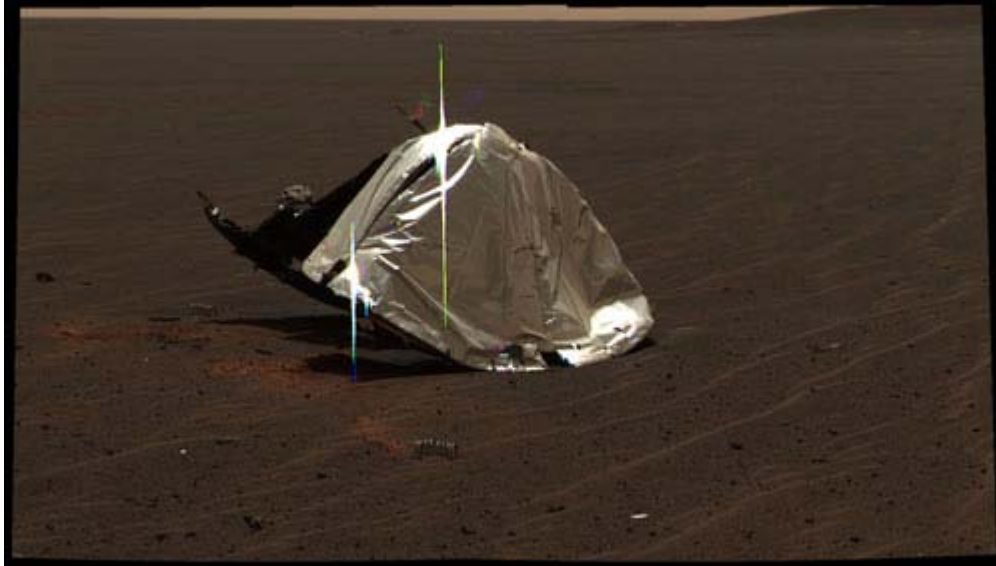
- Search for and characterize a variety of rocks and soils that hold clues to past water activity. In particular, samples sought include those that have minerals deposited by water-related processes such as precipitation, evaporation, sedimentary cementation, or hydrothermal activity.
- Determine the distribution and composition of minerals, rocks, and soils surrounding the landing sites.
- Determine what geologic processes have shaped the local terrain and influenced the chemistry. Such processes could include water or wind erosion, sedimentation, hydrothermal mechanisms, volcanism, and cratering.
- Perform calibration and validation of surface observations made by Mars Reconnaissance Orbiter instruments. This will help determine the accuracy and effectiveness of various instruments that survey Martian geology from orbit.
- Search for iron-containing minerals, and to identify and quantify relative amounts of specific mineral types that contain water or were formed in water, such as iron-bearing carbonates.
- Characterize the mineralogy and textures of rocks and soils to determine the processes that created them.
- Search for geological clues to the environmental conditions that existed when liquid water was present.
- Assess whether those environments were conducive to life.

During the next two decades, NASA will conduct several missions to address whether life ever existed on Mars. The search begins with determining whether the Martian environment was ever suitable for life. Life, as humans understand it, requires water, so the history of water on Mars is critical to finding out if the Martian environment was ever

conducive to life. Although the Mars Exploration Rovers do not have the ability to detect life directly, they offer important information on the habitability of the environment in the planet's history



NASA's Mars Exploration Rover *Spirit* casts a shadow over the trench that the rover is examining with tools on its robotic arm. *Spirit* took this image with its front hazard-avoidance camera on February 21, 2004, during the rover's 48th martian day, or sol 48.



Opportunity's discarded heat shield

History

On January 21, 2004, the Deep Space Network lost contact with *Spirit*, for reasons originally thought to be related to a thunderstorm over Australia. The rover transmitted a message with no data, but later that day missed another communications session with the Mars Global Surveyor. The next day, JPL received a beep from the rover, indicating that it was in fault mode. On January 23, the flight team succeeded in making the rover send. The fault was believed to have been caused by an error in the rover's flash memory subsystem. The rover did not perform any scientific activities for ten days, while engineers updated its software and ran tests. The problem was corrected by reformatting *Spirit's* flash memory and using a software patch to avoid memory overload; *Opportunity* was also upgraded with the patch as a precaution. *Spirit* returned to full scientific operations by February 5.

On March 23, 2004, a news conference was held announcing "major discoveries" of evidence of past liquid water on the Martian surface. A delegation of scientists showed pictures and data revealing a stratified pattern and cross bedding in the rocks of the outcrop inside a crater in Meridiani Planum, landing site of MER-B, *Opportunity*. This suggested that water once flowed in the region. The irregular distribution of chlorine and bromine also suggests that the place was once the shoreline of a salty sea, now evaporated.

On April 8, 2004, NASA announced that it was extending the mission life of the rovers from three to eight months. It immediately provided additional funding of US \$15 million through September, and \$2.8 million per month for continuing operations. Later that month, *Opportunity* arrived at Endurance crater, taking about five days to drive the 200 meters. NASA announced on September 22 that it was extending the mission life of the

rovers for another six months. *Opportunity* was to leave Endurance crater, visit its discarded heat shield, and proceed to Victoria crater. *Spirit* was to attempt to climb to the top of the Columbia Hills.

With the two rovers still functioning well, NASA later announced another 18 month extension of the mission to September 2006. *Opportunity* was to visit the "Etched Terrain" and *Spirit* was to climb a rocky slope toward the top of Husband Hill. On August 21, 2005, *Spirit* reached the summit of Husband Hill after 581 sols and a journey of 4.81 kilometers (2.99 mi).



Spirit's "postcard" view from the summit of Husband Hill: a windswept plateau strewn with rocks, small exposures of outcrop, and sand dunes. The view is to the north, looking down upon the "Tennessee Valley". This approximate true-color composite spans about 90 degrees and consists of eighteen frames captured by the rover's panoramic camera.

Spirit celebrated its one Martian year anniversary (669 sols or 687 Earth days) on November 20, 2005. *Opportunity* celebrated its anniversary on December 12, 2005. At the beginning of the mission, it was expected that the rovers would not survive much longer than 90 Martian days. The Columbia Hills were "just a dream", according to rover driver Chris Leger. *Spirit* explored the semicircular rock formation known as Home Plate. It is a layered rock outcrop that puzzles and excites scientists. It is thought that its rocks are explosive volcanic deposits, though other possibilities exist, including impact deposits or sediment borne by wind or water.

Spirit's front right wheel ceased working on March 13, 2006, while the rover was moving itself to McCool Hill. Its drivers attempted to drag the dead wheel behind Spirit, but this only worked until reaching an impassable sandy area on the lower slopes. Drivers directed *Spirit* to a smaller sloped feature, dubbed "Low Ridge Haven", where it spent the long Martian winter, waiting for spring and increased solar power levels suitable for driving. That September, *Opportunity* reached the rim of Victoria crater, and Spaceflight Now reported that NASA had extended mission for the two rovers through September

2007. On February 6, 2007, *Opportunity* became the first spacecraft to traverse ten kilometers (10,000 meters) on the surface of Mars.

Opportunity was poised to enter Victoria Crater from its perch on the rim of Duck Bay on June 28, 2007, but due to extensive dust storms, it was indefinitely delayed until the dust had cleared and power returned to safe levels. Two months later, *Spirit* and *Opportunity* resumed driving after hunkering down during raging dust storms that limited solar power to a level that nearly caused the permanent failure of both rovers.

On October 1, 2007, both *Spirit* and *Opportunity* entered their fifth mission extension that could possibly extend operations into 2009, allowing the rovers to have spent five years exploring the Martian surface, pending their continued survival.

On August 26, 2008, *Opportunity* began its three-day climb out of Victoria crater amidst concerns that power spikes, similar to those seen on *Spirit* before the failure of its right-front wheel, might prevent it from ever being able to leave the crater if a wheel failed. Project scientist Bruce Banerdt also said, "We've done everything we entered Victoria Crater to do and more." *Opportunity* will return to the plains in order to characterize Meridiani Planum's vast diversity of rocks—some of which may have been blasted out of craters such as Victoria. The rover had been exploring Victoria Crater since September 11, 2007. As of January 2009, the two rovers had collectively sent back 250,000 images and traveled over 21 kilometers (13 mi).

After driving about 3.2 kilometers (2 mi) since it left Victoria crater, *Opportunity* first saw the rim of Endeavour crater on March 7, 2009. It passed the 10-mile mark (16 kilometers) along the way on sol 1897. Meanwhile, at Gusev crater, *Spirit* was dug in deep into the Martian sand, much as *Opportunity* was at Purgatory Dune in 2005.

On January 3 and January 24, 2010, *Spirit* and *Opportunity* marked six years on Mars, respectively. On January 26, NASA announced that *Spirit* will be used as a stationary research platform after several months of unsuccessful attempts to free the rover from soft sand.

NASA announced on March 24, 2010, that *Opportunity*, which has an estimated remaining drive distance of 12 km to Endeavour Crater, has traveled over 20 km since the start of its mission. Each rover was designed with a mission driving distance goal of just 600 meters. One week later, they announced that *Spirit* may have gone into hibernation for the Martian winter and might not wake up again for months.

On September 8, 2010, it was announced that *Opportunity* had reached the halfway point of the 19-kilometer journey between Victoria crater and Endeavour crater.

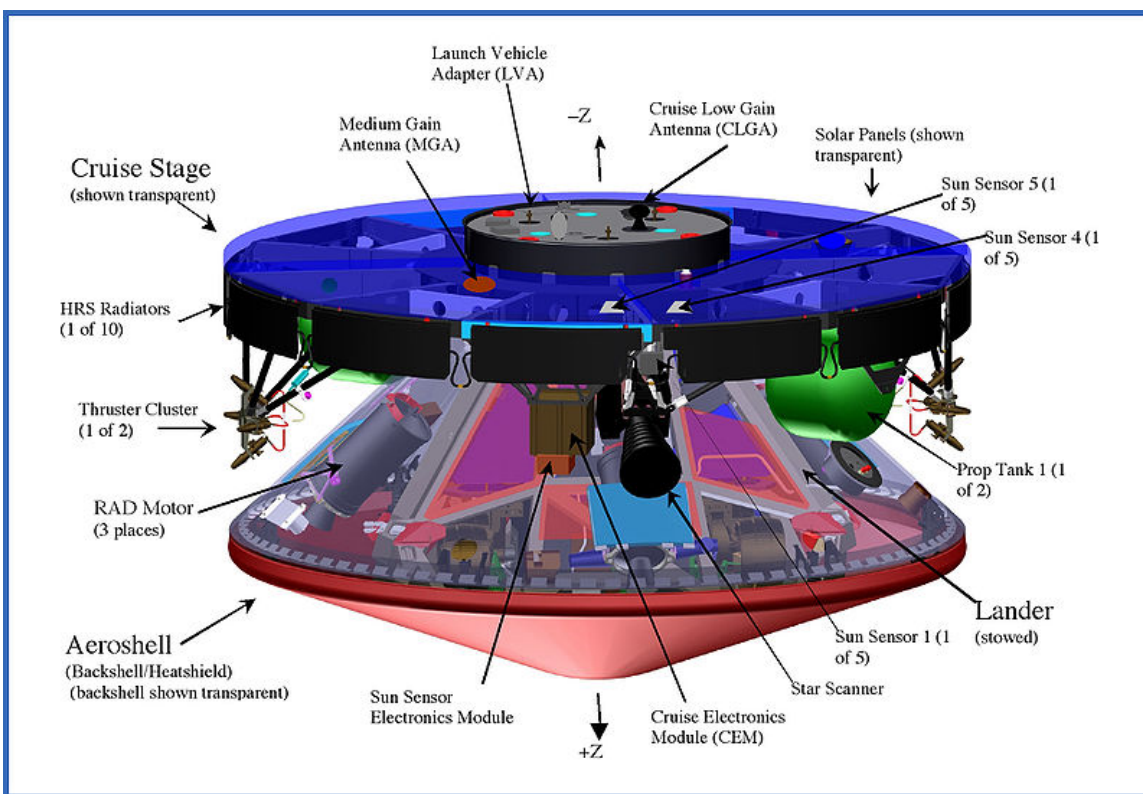
Spacecraft design



Delta II Heavy lifting off with MER-A on June 10, 2003



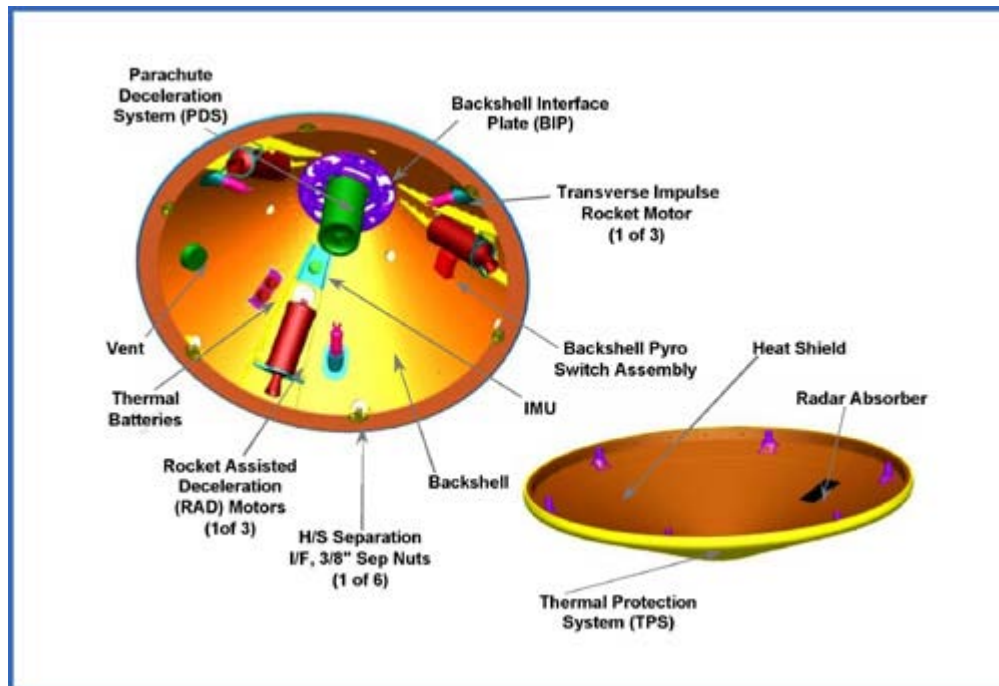
Delta II Heavy (7925H-9.5) lifting off from pad 17-B carrying MER-B



MER cruise stage diagram (Courtesy NASA/JPL-Caltech)



Cruise stage of *Opportunity* rover



Overview of the Mars Exploration Rover aeroshell



MER launch configuration, break apart illustration

The Mars Exploration Rover was designed to be stowed in the nose of a Delta II rocket. Each spacecraft consists of several components:

- Rover: 185 kg (408 lb)
- Lander: 348 kg (767 lb)
- Backshell / Parachute: 209 kg (461 lb)
- Heat Shield: 78 kg (172 lb)
- Cruise Stage: 193 kg (425 lb)
- Propellant: 50 kg (110 lb)
- Instruments: 5 kg (11 lb)

Total mass is 1,063 kg (2,343 lb).

Cruise stage

The cruise stage is the component of the spacecraft that is used for travel from Earth to Mars. It is very similar to the Mars Pathfinder in design and is approximately 2.65 meters (8.7 ft) in diameter and 1.6 m (5.2 ft) tall, including the entry vehicle (see below).

The primary structure is aluminium with an outer ring of ribs covered by the solar panels, which are about 2.65 m (8.7 ft) in diameter. Divided into five sections, the solar arrays can provide up to 600 watts of power near Earth and 300 W at Mars.

Heaters and multi-layer insulation keep the electronics "warm". A freon system removes heat from the flight computer and communications hardware inside the rover so they do not overheat. Cruise avionics systems allow the flight computer to interface with other electronics, such as the sun sensors, star scanner and heaters.

Navigation

The star scanner (with a backup system) and sun sensor allowed the spacecraft to know its orientation in space by analyzing the position of the Sun and other stars in relation to itself. Sometimes the craft could be slightly off course; this was expected, given the 500 million kilometer (320 million mile) journey. Thus navigators planned up to six trajectory correction maneuvers, along with health checks.

To ensure the spacecraft arrived at Mars in the right place for its landing, two light-weight, aluminium-lined tanks carried about 31 kg (about 68 lb) of hydrazine propellant. Along with cruise guidance and control systems, the propellant allowed navigators to keep the spacecraft on course. Burns and pulse firings of the propellant allowed three types of maneuvers:

- An axial burn uses pairs of thrusters to change spacecraft velocity;
- A lateral burn uses two "thruster clusters" (four thrusters per cluster) to move the spacecraft "sideways" through seconds-long pulses;
- Pulse mode firing uses coupled thruster pairs for spacecraft precession maneuvers (turns).

Communication

The spacecraft used a high-frequency X band radio wavelength to communicate, which allowed for less power and smaller antennas than many older craft, which used S band.

Navigators sent commands through two antennas on the cruise stage: a **cruise low-gain antenna** mounted inside the inner ring, and a **cruise medium-gain antenna** in the outer ring. The low-gain antenna was used close to Earth. It is omni-directional, so the transmission power that reached Earth fell faster with increasing distance. As the craft moved closer to Mars, the Sun and Earth moved closer in the sky as viewed from the craft, so less energy reached Earth. The spacecraft then switched to the medium-gain antenna, which directed the same amount of transmission power into a tighter beam toward Earth.

During flight, the spacecraft was spin-stabilized with a spin rate of two revolutions per minute (rpm). Periodic updates kept antennas pointed toward Earth and solar panels toward the Sun.

Aeroshell

The aeroshell maintained a protective covering for the lander during the seven month voyage to Mars. Together with the lander and the rover, it constituted the "entry vehicle". Its main purpose was to protect the lander and the rover inside it from the intense heat of entry into the thin Martian atmosphere. It was based on the Mars Pathfinder and Mars Viking designs.

Parts

The aeroshell was made of two main parts: a heat shield and a backshell. The heat shield was flat and brownish, and protected the lander and rover during entry into the Martian atmosphere and acted as the first aerobrake for the spacecraft. The backshell was large, cone-shaped and painted white. It carried the parachute and several components used in later stages of entry, descent, and landing, including:

- A parachute (stowed at the top of the backshell);
- The backshell electronics and batteries that fire off pyrotechnic devices like separation nuts, rockets and the parachute mortar;
- A Litton LN-200 Inertial Measurement Unit (IMU), which monitors and reports the orientation of the backshell as it swings under the parachute;
- Three large solid rocket motors called RAD rockets (Rocket Assisted Descent), each providing about a ton of force (10 kilonewtons) for about 4 seconds;
- Three small solid rockets called TIRS (mounted so that they aim horizontally out the sides of the backshell) that provide a small horizontal kick to the backshell to help orient the backshell more vertically during the main RAD rocket burn.

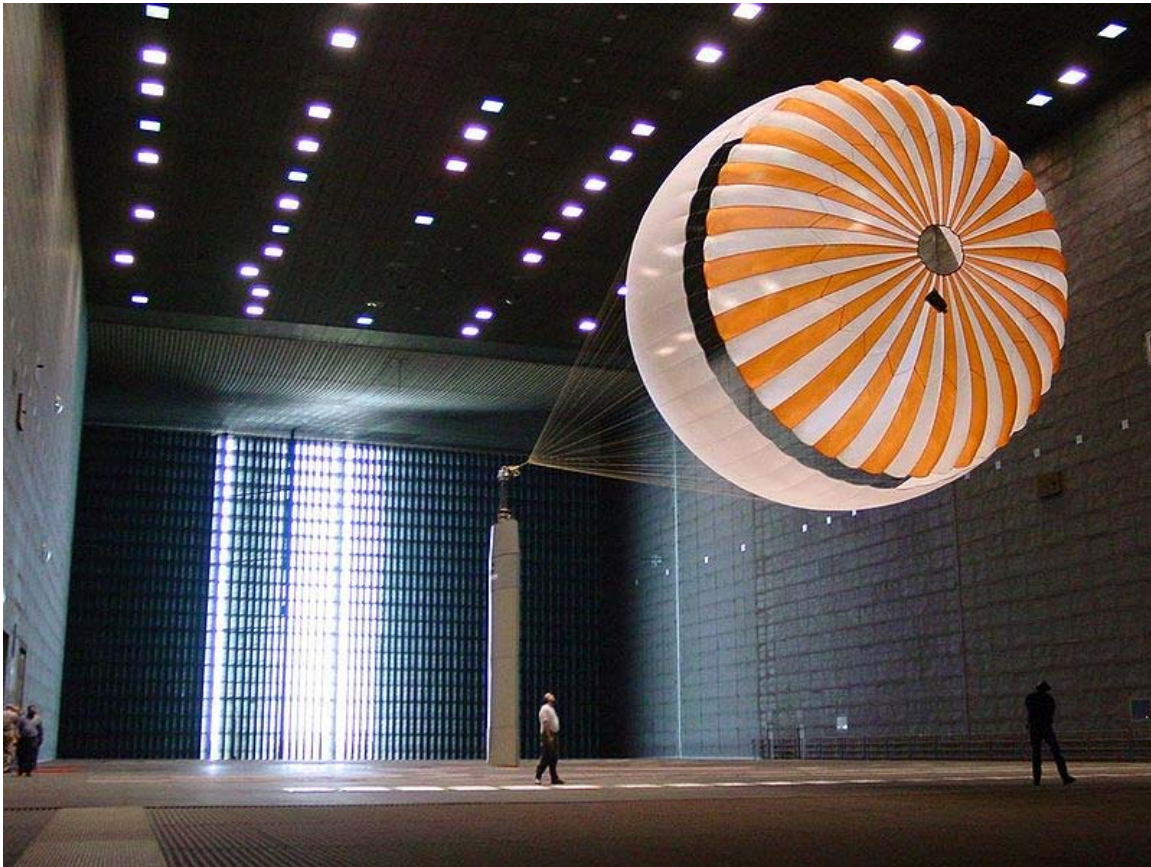
Composition

Built by the Lockheed Martin Astronautics Co. in Denver, Colorado, the aeroshell is made of an aluminium honeycomb structure sandwiched between graphite-epoxy face sheets. The outside of the aeroshell is covered with a layer of phenolic honeycomb. This honeycomb is filled with an ablative material (also called an "ablator"), that dissipates heat generated by atmospheric friction.

The ablator itself is a unique blend of cork wood, binder and many tiny silica glass spheres. It was invented for the heat shields flown on the Viking Mars lander missions. A similar technology was used in the first US manned space missions Mercury, Gemini and Apollo. It was specially formulated to react chemically with the Martian atmosphere during entry and carry heat away, leaving a hot wake of gas behind the vehicle. The vehicle slowed from 19000 km/h (about 12000 mph) to about 1600 km/h (1000 mph) in about a minute, producing about 60 m/s^2 (6 g) of acceleration on the lander and rover.

The backshell and heat shield are made of the same materials, but the heat shield has a thicker, 1/2 inch (12.7 mm), layer of the ablator. Instead of being painted, the backshell was covered with a very thin aluminized PET film blanket to protect it from the cold of deep space. The blanket vaporized during entry into the Martian atmosphere.

Parachute



Mars Exploration Rover's parachute test

The parachute helped slow the spacecraft during entry, descent, and landing. It is located in the backshell.

Design

The 2003 parachute design was part of a long-term Mars parachute technology development effort and is based on the designs and experience of the Viking and Pathfinder missions. The parachute for this mission is 40% larger than Pathfinder's because the largest load for the Mars Exploration Rover is 80 to 85 kilonewtons (kN) or 18,000 to 19,000 lbf (85 kN) when the parachute fully inflates. By comparison, Pathfinder's inflation loads were approximately 35 kN (about 8,000 lbf). The parachute was designed and constructed in South Windsor, Connecticut by Pioneer Aerospace, the company that also designed the parachute for the *Stardust* mission.

Composition

The parachute is made of two durable, lightweight fabrics: polyester and nylon. A triple bridle made of Kevlar connects the parachute to the backshell.

The amount of space available on the spacecraft for the parachute is so small that the parachute had to be pressure-packed. Before launch, a team tightly folded the 48 suspension lines, three bridle lines, and the parachute. The parachute team loaded the parachute in a special structure that then applied a heavy weight to the parachute package several times. Before placing the parachute into the backshell, the parachute was heat set to sterilize it.

Connected systems



Descent is halted by retrorockets and lander is dropped 10m (30 ft) to the surface in this computer generated impression.

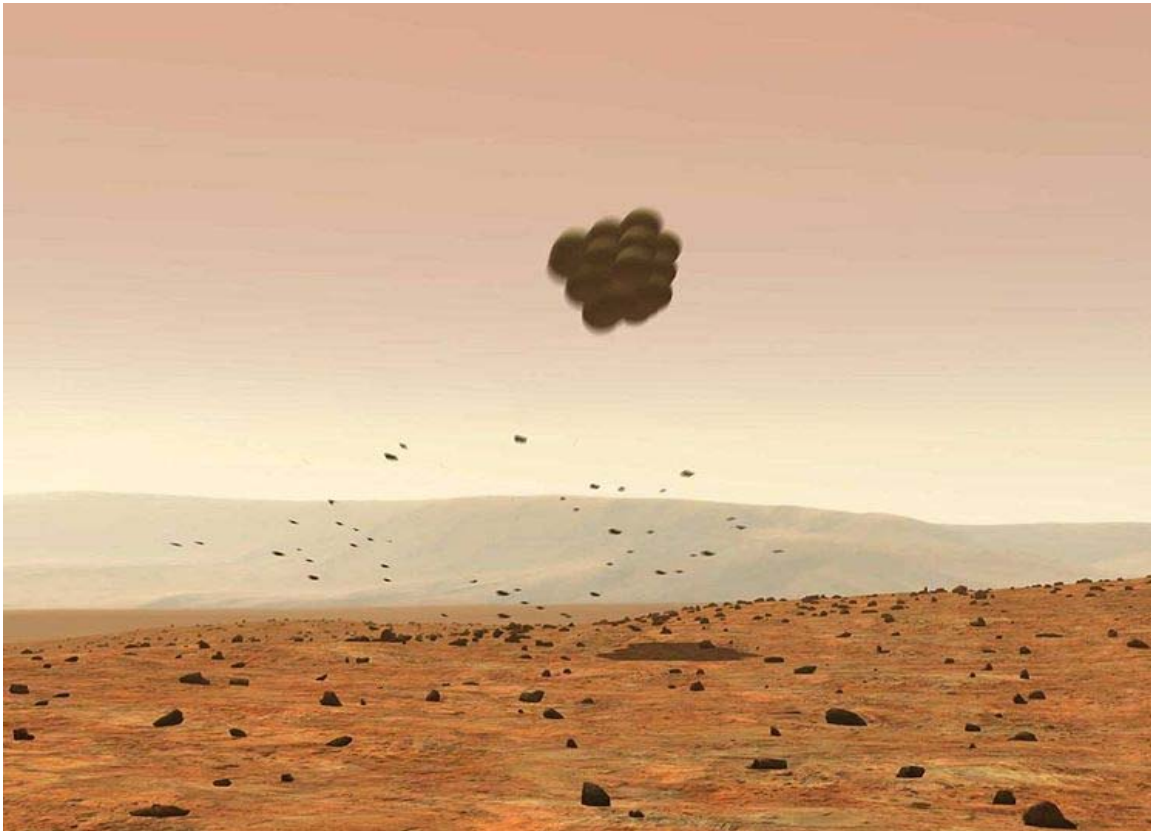
Zylon Bridles: After the parachute was deployed at an altitude of about 10 km (6 miles) above the surface, the heatshield was released using 6 separation nuts and push-off springs. The lander then separated from the backshell and "rappelled" down a metal tape on a centrifugal braking system built into one of the lander petals. The slow descent down the metal tape placed the lander in position at the end of another bridle (tether), made of a nearly 20 m (65 ft) long braided Zylon.

Zylon is an advanced fiber material, similar to Kevlar, that is sewn in a webbing pattern (like shoelace material) to make it stronger. The Zylon bridle provides space for airbag deployment, distance from the solid rocket motor exhaust stream, and increased stability. The bridle incorporates an electrical harness that allows the firing of the solid rockets from the backshell as well as provides data from the backshell inertial measurement unit (which measures rate and tilt of the spacecraft) to the flight computer in the rover.

Rocket assisted descent (RAD) motors: Because the atmospheric density of Mars is less than 1% of Earth's, the parachute alone could not slow down the Mars Exploration Rover enough to ensure a safe, low landing speed. The spacecraft descent was assisted by rockets that brought the spacecraft to a dead stop 10–15 m (30–50 ft) above the Martian surface.

Radar altimeter unit: A radar altimeter unit was used to determine the distance to the Martian surface. The radar's antenna is mounted at one of the lower corners of the lander tetrahedron. When the radar measurement showed the lander was the correct distance above the surface, the Zylon bridle was cut, releasing the lander from the parachute and backshell so that it was free and clear for landing. The radar data also enabled the timing sequence on airbag inflation and backshell RAD rocket firing.

Airbags



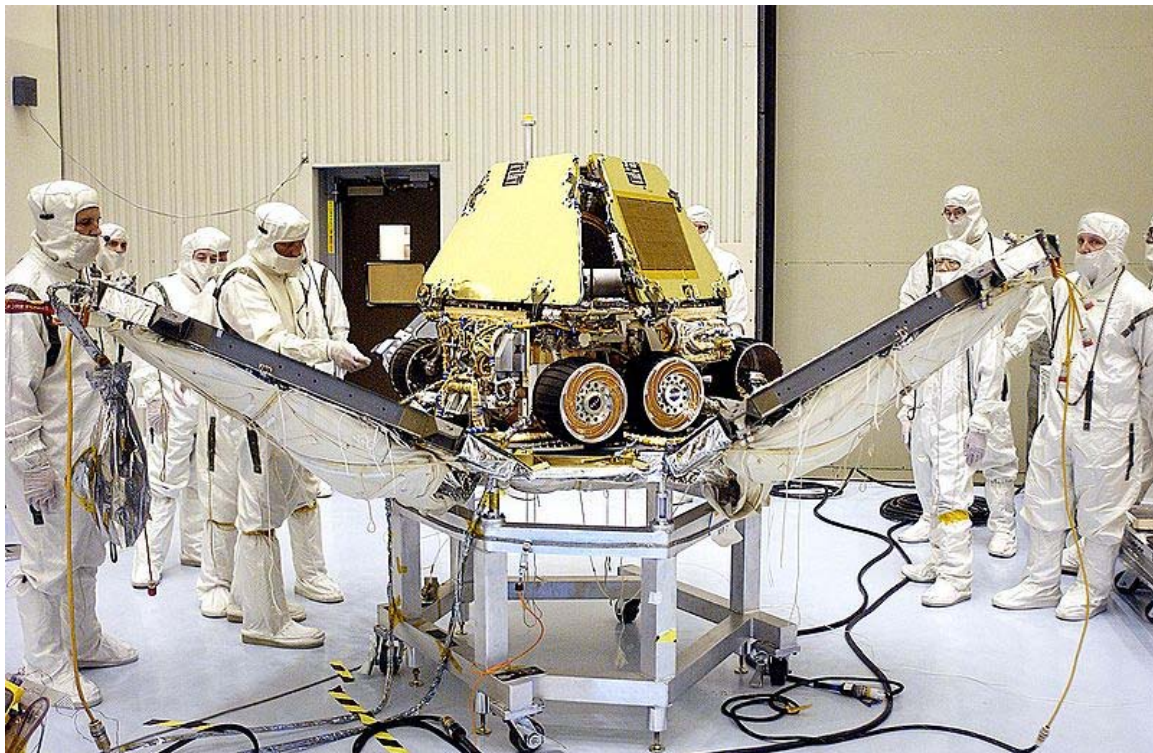
Artist's concept of inflated airbags

Airbags used in the Mars Exploration Rover mission are the same type that Mars Pathfinder used in 1997. They had to be strong enough to cushion the spacecraft if it landed on rocks or rough terrain and allow it to bounce across Mars' surface at freeway speeds after landing. The airbags had to be inflated seconds before touchdown and deflated once safely on the ground.

The airbags were made of Vectran, like those on Pathfinder. Vectran has almost twice the strength of other synthetic materials, such as Kevlar, and performs better in cold temperatures. Six 100 denier (10 mg/m) layers of Vectran protected one or two inner bladders of Vectran in 200 denier (20 mg/m). Using 100 denier (10 mg/m) leaves more fabric in the outer layers where it is needed, because there are more threads in the weave.

Each rover used four airbags with six lobes each, all of which were connected. Connection was important, since it helped abate some of the landing forces by keeping the bag system flexible and responsive to ground pressure. The airbags were not attached directly to the rover, but were held to it by ropes crisscrossing the bag structure. The ropes gave the bags shape, making inflation easier. While in flight, the bags were stowed along with three gas generators that are used for inflation.

Lander



MER lander petals opening (Courtesy NASA/JPL-Caltech)

The spacecraft lander is a protective "shell" that houses the rover, and together with the airbags, protects it from the forces of impact.

The lander is a tetrahedron shape, whose sides open like petals. It is strong and light, and made of beams and sheets. The beams consist of layers of graphite fiber woven into a fabric that is lighter than aluminium and more rigid than steel. Titanium fittings are glued and fitted onto the beams to allow it to be bolted together. The rover was held inside the lander by bolts and special nuts that were released after landing with small explosives.

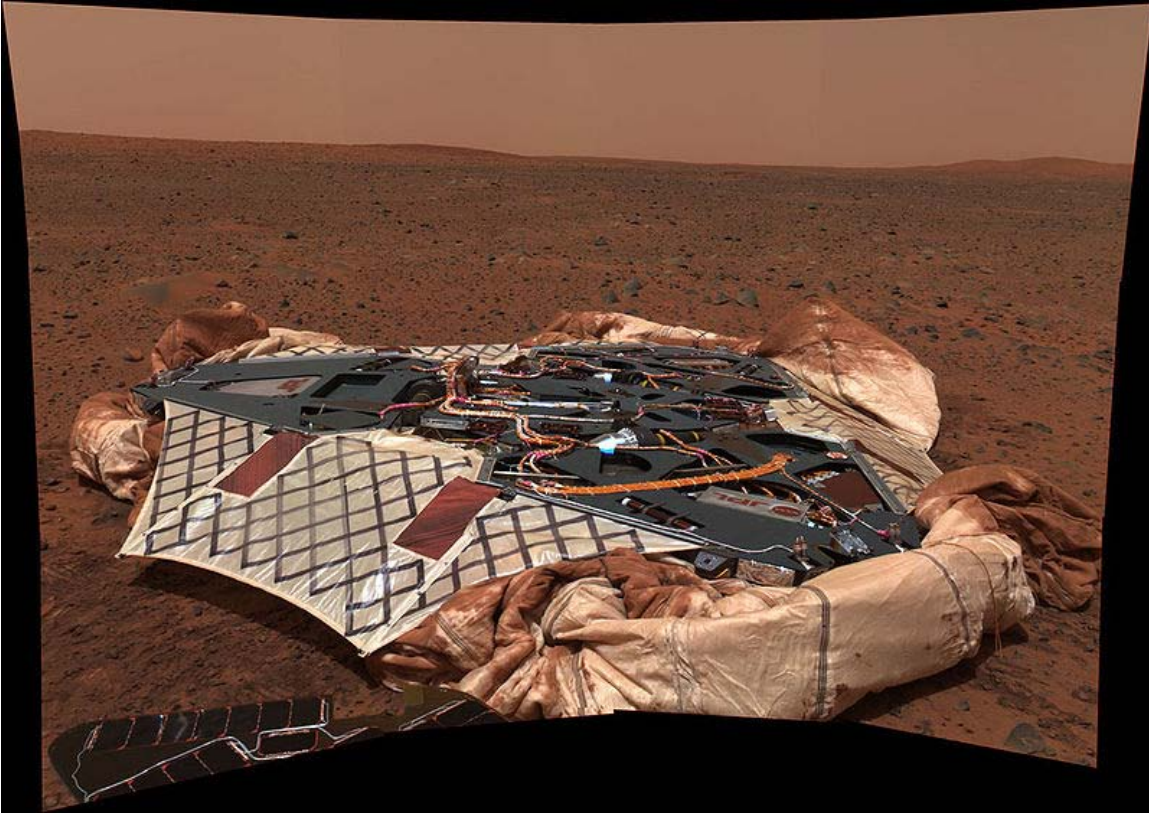
Uprighting

After the lander stopped bouncing and rolling on the ground, it came to rest on the base of the tetrahedron or one of its sides. The sides then opened to make the base horizontal and the rover upright. The sides are connected to the base by hinges, each of which has a motor strong enough to lift the lander. The rover plus lander has a mass of about 533 kilograms (1,175 pounds). The rover alone weighs about 185 kg (408 lb). The gravity on Mars is about 38% of Earth's, so the motor does not need to be as powerful as it would on Earth.

The rover contains accelerometers to detect which way is down (toward the surface of Mars) by measuring the pull of gravity. The rover computer then commanded the correct lander petal to open to place the rover upright. Once the base petal was down and the rover was upright, the other two petals were opened.

The petals initially opened to an equally flat position, so all sides of the lander were straight and level. The petal motors are strong enough so that if two of the petals come to rest on rocks, the base with the rover would be held in place like a bridge above the ground. The base will hold at a level even with the height of the petals resting on rocks, making a straight flat surface throughout the length of the open, flattened lander. The flight team on Earth could then send commands to the rover to adjust the petals and create a safe path for the rover to drive off the lander and onto the Martian surface without dropping off a steep rock.

Moving the payload onto Mars



Spirit's lander on Mars

The moving of the rover off the lander is called the egress phase of the mission. The rover must avoid having its wheels caught in the airbag material or falling off a sharp incline. To help this, a retraction system on the petals slowly drags the airbags toward the lander before the petals open. Small ramps on the petals fan out to fill spaces between the petals. They cover uneven terrain, rock obstacles, and airbag material, and form a circular area from which the rover can drive off in more directions. They also lower the step that the rover must climb down. They are nicknamed "batwings", and are made of Vectran cloth.

About three hours were allotted to retract the airbags and deploy the lander petals.

Rover design



Mars Exploration Rover vs. Sojourner rover (Courtesy NASA/JPL-Caltech)

The rovers are six-wheeled, solar-powered robots that stand 1.5 m (4.9 ft) high, 2.3 m (7.5 ft) wide and 1.6 m (5.2 ft) long. They weigh 180 kg (400 lb), 35 kg (80 lb) of which is the wheel and suspension system.

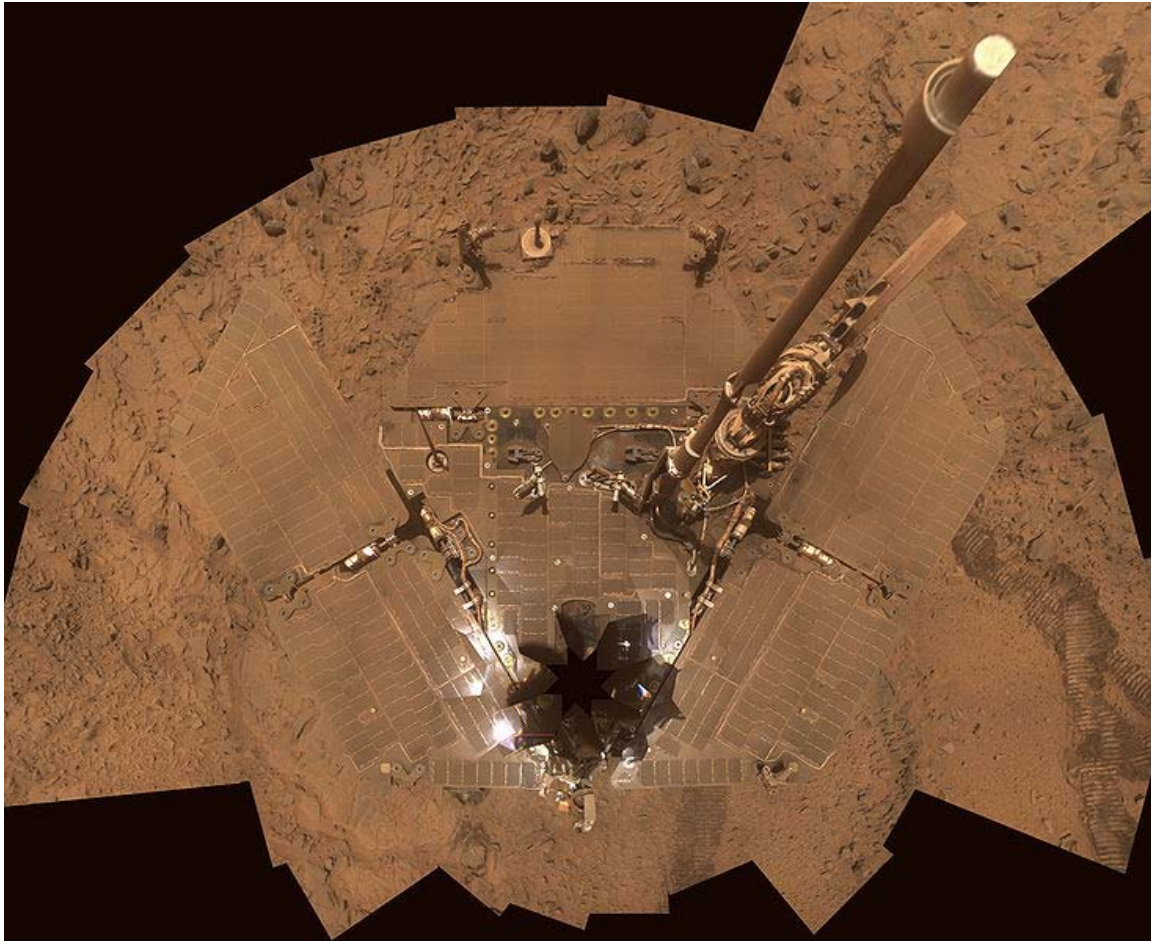
Drive system

Each rover has six wheels mounted on a rocker-bogie suspension system that ensures wheels remain on the ground while driving over rough terrain. The design reduces the range of motion of the rover body by half, and allows the rover to go over obstacles or through holes that are more than a wheel diameter (250 mm or 10 inches) in size. Each wheel also has cleats, providing grip for climbing in soft sand and scrambling over rocks.

Each wheel has its own motor. The two front and two rear wheels each have individual steering motors. This allows the vehicle to turn in place, a full revolution, and to swerve and curve, making arching turns. The rover is designed to withstand a tilt of 45 degrees in any direction without overturning. However, the rover is programmed through its "fault protection limits" in its hazard avoidance software to avoid exceeding tilts of 30 degrees.

Each rover can spin one of its front wheels in place to grind deep into the terrain. It is to remain motionless while the digging wheel is spinning. The rovers have a top speed on flat hard ground of 50 mm/s (2 in/s). The average speed is 10 mm/s, because its hazard avoidance software causes it to stop every 10 seconds for 20 seconds to observe and understand the terrain into which it has driven.

Power and electronic systems



Circular projection showing MER-A *Spirit's* solar panels covered in dust in October 2007 on Mars. Unexpected Cleaning events have periodically increased power.

When fully illuminated, the rover triplejunction solar arrays generate about 140 watts for up to four hours per Martian day (sol). The rover needs about 100 watts to drive. Its power system includes two rechargeable lithium ion batteries weighing 7.15 kg (16 pounds) each, that provide energy when the sun is not shining, especially at night. Over time, the batteries will degrade and will not be able to recharge to full capacity.

For comparison, the future Mars Science Laboratory's power system is composed of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) produced by Boeing. The MMRTG is designed to provide 125W of electrical power at the start of the mission,

falling to 100W after 14 years of service. It will be used to power the MSL's many systems and instruments. Solar panels were also considered for the MSL, but RTGs provide constant power, regardless of the time of day, and thus the versatility to work in dark environments and high latitudes where solar energy is not readily available. The MSL will generate 2.5 kilowatt hours per day, compared to the Mars Exploration Rovers, which can generate about 0.6 kilowatt hours per day.

It was thought that by the end of the 90-sol mission, the capability of the solar arrays to generate power would likely be reduced to about 50 watts. This was due to anticipated dust coverage on the solar arrays, and the change in season. Over three Earth years later, however, the rovers' power supplies hovered between 300 watt-hours and 900 watt-hours per day, depending on dust coverage. Cleaning events (dust removal by wind) have occurred more often than NASA expected, keeping the arrays relatively free of dust and extending the life of the mission. During a 2007 global dust storm on Mars, both rovers experienced some of the lowest power of the mission; *Opportunity* dipped to 128 watt-hours. In November 2008, Spirit had overtaken this low-energy record with a production of 89 watt-hours, due to dust storms in the region of Gusev crater.

The rovers run a VxWorks embedded operating system on a radiation-hardened 20 MHz RAD6000 CPU with 128 MB of DRAM with error detection and correction and 3 MB of EEPROM. Each rover also has 256 MB of flash memory. To survive during the various mission phases, the rover's vital instruments must stay within a temperature of $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$ to $104\text{ }^{\circ}\text{F}$). At night, the rovers are heated by eight radioisotope heater units (RHU), which each continuously generate 1 W of thermal energy from the decay of radioisotopes, along with electrical heaters that operate only when necessary. A sputtered gold film and a layer of silica aerogel are used for insulation.

Communication

The rover has a low-gain and a high-gain antenna. The low-gain antenna is omnidirectional, and transmits data at a low rate to Deep Space Network (DSN) antennas on Earth. The high-gain antenna is directional and steerable, and can transmit data to Earth at a higher rate. The rovers also use the low-gain antennas to communicate with spacecraft orbiting Mars, the Mars Odyssey and (before its failure) the Mars Global Surveyor. The orbiters relay data from and to Earth; most data to Earth is relayed through Odyssey. The orbiters are closer to the rovers than the antennas on Earth, and have a view of Earth for much longer than the rovers. The orbiters communicate with the rovers using UHF antennas, which have shorter range than the low and high-gain antennas. One UHF antenna is on the rover, and one is on a petal of the lander to aid in gaining information during the critical landing event.

The rovers have a total of 9 cameras, which produce 1024-pixel by 1024-pixel images at 12 bits per pixel, but most navigation camera images and image thumbnails are truncated to 8 bits per pixel to conserve memory and transmission time. All images are then compressed using ICER before being stored and sent to Earth. Navigation, thumbnail, and many other image types are compressed to approximately 0.8 to 1.1 bits/pixel. Lower

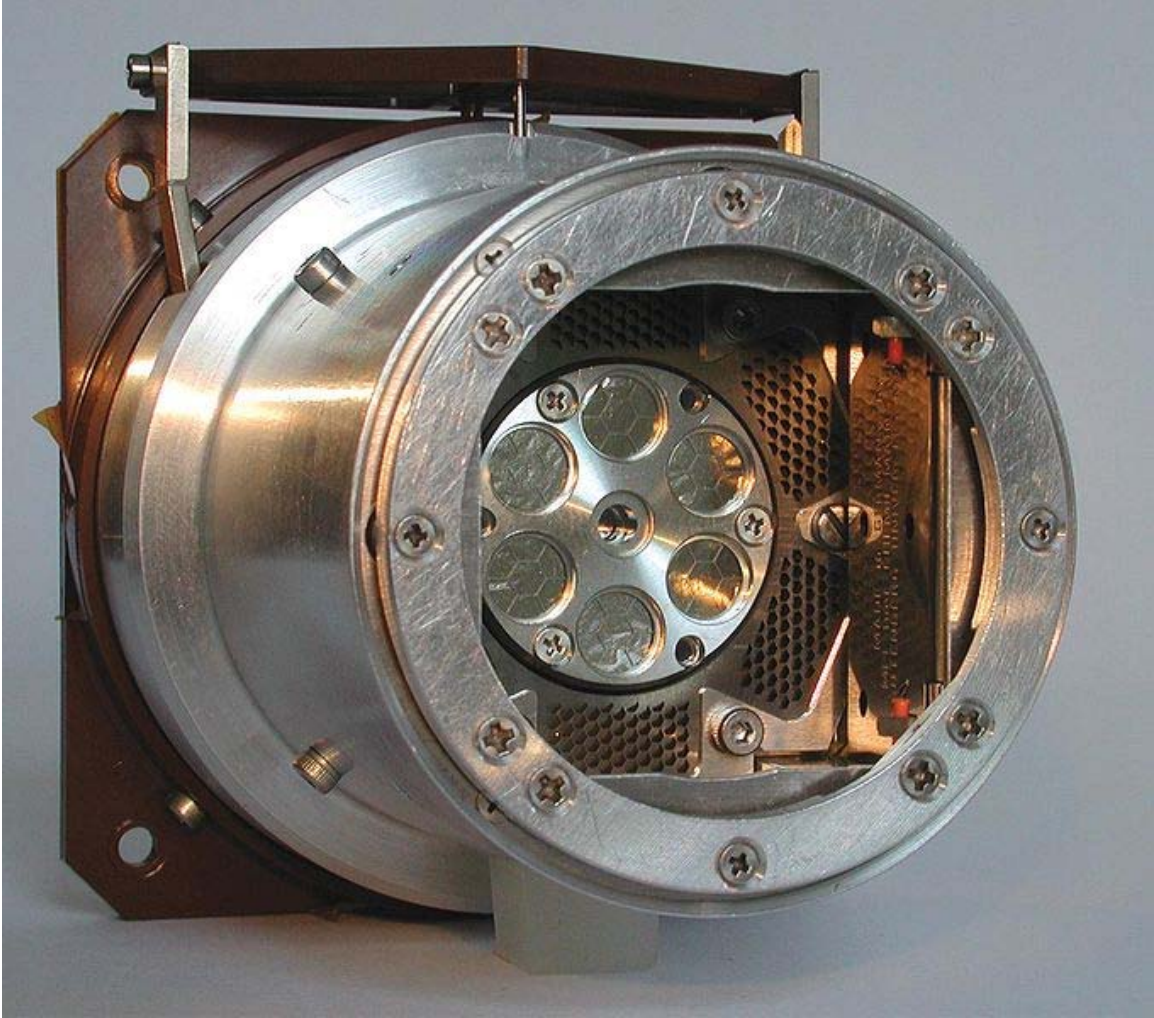
bit rates (less than 0.5 bit/pixel) are used for certain wavelengths of multi-color panoramic images.

ICER is based on wavelets, and was designed specifically for deep-space applications. It produces progressive compression, both lossless and lossy, and incorporates an error-containment scheme to limit the effects of data loss on the deep-space channel. It outperforms the lossy JPEG image compressor and the lossless Rice compressor used by the Mars Pathfinder mission.

Scientific instrumentation



Panoramic Camera (Pancam)



Alpha particle X-Ray Spectrometer (APXS) (Courtesy NASA/JPL-Caltech)



Rock Abrasion Tool (RAT)

The rover has various instruments. Three are mounted on one assembly:

- Panoramic Camera (Pancam), for determining the texture, color, mineralogy, and structure of the local terrain.
- Navigation Camera (Navcam), that has higher field of view but lower resolution and is monochromatic, for navigation and driving.
- A mirror for the Miniature Thermal Emission Spectrometer (Mini-TES), which identifies promising rocks and soils for closer examination, and determines the processes that formed them. It was built by Arizona State University.

The cameras are mounted 1.5 meters high on the Pancam Mast Assembly. One motor turns the assembly horizontally a whole revolution. Another points the cameras vertically, at most straight up or down. A third motor points the Mini-TES, up to 30° above the horizon and 50° below. The assembly was built by Ball Aerospace & Technologies Corp., Boulder, Colorado, as was the High-Gain Antenna Gimbal (HGAG).

Four monochromatic hazard cameras (Hazcams) are mounted on the rover's body, two in front and two behind.

The instrument deployment device (IDD), also called the rover arm, holds the following:

- Mössbauer spectrometer (MB) MIMOS II, developed by Dr. Göstar Klingelhöfer at the Johannes Gutenberg University in Mainz, Germany, is used for close-up investigations of the mineralogy of iron-bearing rocks and soils.
- Alpha Particle X-Ray Spectrometer (APXS), developed by the Max Planck Institute for Chemistry in Mainz, Germany, is used for close-up analysis of the abundances of elements that make up rocks and soils.
- Magnets, for collecting magnetic dust particles, developed by Jens Martin Knudsen's group at the Niels Bohr Institute, Copenhagen. The particles are analyzed by the Mössbauer Spectrometer and X-ray Spectrometer to help determine the ratio of magnetic particles to non-magnetic particles and the composition of magnetic minerals in airborne dust and rocks that have been ground by the Rock Abrasion Tool. There are also magnets on the front of the rover, which are studied extensively by the Mössbauer spectrometer.
- Microscopic Imager (MI) for obtaining close-up, high-resolution images of rocks and soils. Development was led by Ken Herkenhoff's team at the USGS Astrogeology Research Program.
- Rock Abrasion Tool (RAT), developed by Honeybee Robotics, for removing dusty and weathered rock surfaces and exposing fresh material for examination by instruments on-board.

The robotic arm is able to place instruments directly up against rock and soil targets of interest.

Naming of *Spirit* and *Opportunity*

The *Spirit* and *Opportunity* rovers were named through a student essay competition. The winning entry was by Sofi Collis, a third-grade Russian-American student from Arizona.

I used to live in an orphanage. It was dark and cold and lonely. At night, I looked up at the sparkly sky and felt better. I dreamed I could fly there. In America, I can make all my dreams come true. Thank you for the 'Spirit' and the 'Opportunity.'

— Sofi Collis, age 9

Prior to this, during the development and building of the rovers, they were known as MER-1 (*Opportunity*) and MER-2 (*Spirit*). Internally, NASA also uses the mission designations MER-A (*Spirit*) and MER-B (*Opportunity*) based on the order of landing on Mars (Spirit first then Opportunity).

Test rovers



Rover team members simulate *Spirit* in a Martian sandtrap

The Jet Propulsion Laboratory maintains a pair of rovers at its location in Pasadena for testing and modeling of situations on Mars. One test rover, weighing approximately 180 kilograms (400 lb), is fully instrumented and nearly identical to *Spirit* and *Opportunity*. Another test version is identical in size and drive characteristics but does not include all instruments. It weighs in at 80 kilograms (180 lb), much closer to the weight of *Spirit* and *Opportunity* in the reduced gravity of Mars. These rovers were used in 2009 for a simulation of the incident in which *Spirit* became trapped in soft soil.

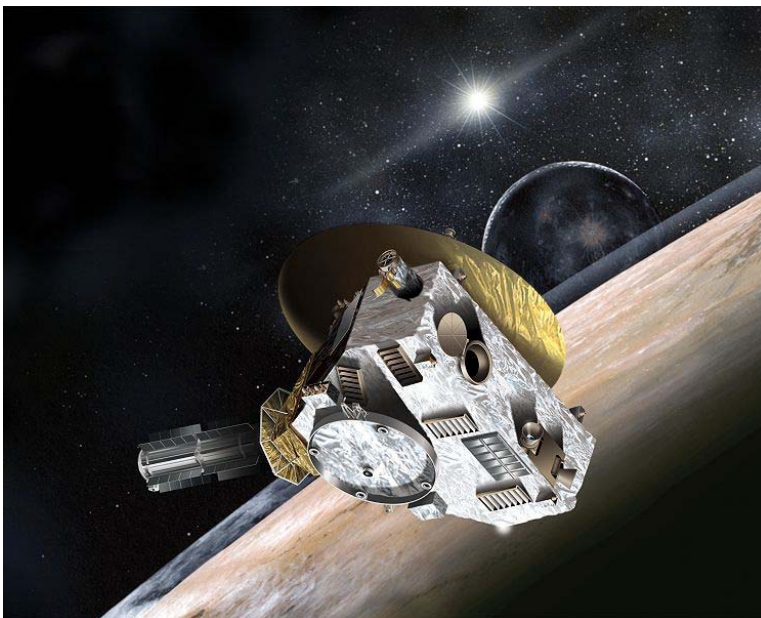
SAP

The NASA team uses a software application called *SAP* to view images collected from the rover, and to plan its daily activities. There is a version available to the public called Maestro.

Chapter 7

New Horizons

New Horizons



Operator	NASA
Major contractors	APL, SwRI
Mission type	Flyby
Flyby of	APL, Jupiter, Pluto, Charon, Hydra, Nix
Flyby date	2015-07-14 (projected)
Launch date	2006-01-19 19:00:00 UTC (4 years, 11 months, and 26 days elapsed)
Launch vehicle	Atlas V 551
Launch site	Launch Complex 41 Cape Canaveral Air Force Station

	In transit (Pluto)
	(4 years, 11 months, and 26 days elapsed)
Mission duration	APL flyby (completed 2006-06-13)
	Jupiter flyby (completed 2007-02-28)
COSPAR ID	2006-001A
Homepage	pluto.jhuapl.edu
Mass	478 kg (1,050 lb)
Power	228 W (RTG)

Orbital elements

Inclination	negligible As of 2010
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New Horizons is a NASA robotic spacecraft mission currently en route to the dwarf planet Pluto. It is expected to be the first spacecraft to fly by and study Pluto and its moons, Charon, Nix, and Hydra. NASA may also approve flybys of one or more other Kuiper belt objects.

New Horizons was launched on January 19, 2006, directly into an Earth-and-solar-escape trajectory. It had an Earth-relative velocity of about 16.26 km/s (58,536 km/h; 36,373 mph) after its last engine shut down. Thus, it left Earth at the fastest launch speed ever recorded for a man-made object. *New Horizons* flew by Jupiter on February 28, 2007, and the orbit of Saturn on June 8, 2008; it is projected to arrive at Pluto on July 14, 2015, after which it will continue into the Kuiper belt.

Background



New Horizons on the launchpad

New Horizons is the first mission in NASA's New Frontiers mission category, larger and more expensive than Discovery missions but smaller than the Flagship Program. The cost of the mission (including spacecraft and instrument development, launch vehicle, mission operations, data analysis, and education/public outreach) is approximately \$650 million over 15 years (from 2001 to 2016). An earlier proposed Pluto mission – Pluto Kuiper Express – was cancelled by NASA in 2000 for budgetary reasons.

The *New Horizons* craft was built primarily by Southwest Research Institute (SwRI) and the Johns Hopkins Applied Physics Laboratory (APL). The mission's principal investigator is Alan Stern (NASA Associate Administrator, formerly of the Southwest Research Institute).

Overall control, after separation from the launch vehicle, is performed at Mission Operations Center (MOC) at the Applied Physics Laboratory. The science instruments are operated at the Clyde Tombaugh Science Operations Center (T-SOC) in Boulder, Colorado. Navigation, which is not real-time, is performed at various contractor facilities; KinetX is the lead on the New Horizons navigation team and is responsible for planning trajectory adjustments as the spacecraft speeds toward the outer Solar System.

New Horizons was originally planned as a voyage to what was then the only unexplored planet in the Solar System. When the spacecraft was launched, Pluto was still classified as a planet, later to be reclassified as a dwarf planet by the International Astronomical Union (IAU). However, some members of the New Horizons team, including Alan Stern, disagree with the IAU definition and therefore still describe Pluto as the ninth planet. Pluto's newly-discovered satellites, Nix and Hydra, also have a connection with the spacecraft: the first letters of their names, **N** and **H**, are the initials of "New Horizons". The moons' discoverers chose these names for this reason, in addition to Nix and Hydra's relationship to the mythological Pluto.

In addition to the scientific equipment, there are several cultural artifacts traveling with the spacecraft. These include a collection of 434,738 names stored on a compact disc, a piece of Scaled Composites, *SpaceShipOne*, and an American flag, along with other mementos. One of the trim weights on the spacecraft is a Florida state quarter.

In homage to the discovery of the dwarf planet the probe will visit, approximately one ounce of the ashes of Pluto discoverer Clyde Tombaugh are aboard the spacecraft, while one of the science packages (a dust counter) is named after Venetia Burney, who as a child was responsible for naming the dwarf planet.

Launch



New Horizons at lift-off

The launch of *New Horizons* was originally scheduled for January 11, 2006, but was initially delayed until January 17 to allow for borescope inspections of the Atlas rocket's kerosene tank. Further delays related to low cloud ceiling conditions downrange, and high winds and technical difficulties - unrelated to the rocket itself - prevented launch for a further two days. The probe finally lifted off from Pad 41 at Cape Canaveral Air Force Station, Florida, directly south of Space Shuttle Launch Complex 39, at 14:00 EST on January 19, 2006.



Space Launch Complex 41 during *New Horizons* launch

The Centaur second stage reignited at 14:30 EST (19:30 UTC), successfully sending the probe out of Earth orbit. *New Horizons* took only nine hours to reach the Moon's orbit, passing lunar orbit before midnight EST that day.

Although there were backup launch opportunities in February 2006 and February 2007, only the first 23 days of the 2006 window permitted the Jupiter fly-by. Any launch outside that period would have forced the spacecraft to fly a slower trajectory directly to Pluto, delaying its encounter by 2–4 years.

The craft was launched by a Lockheed Martin Atlas V 551 rocket, with a Boeing Star 48B third stage added to increase the heliocentric (escape) speed. This was the first launch of the 551 configuration of the Atlas V, as well as the first Atlas V launch with an additional third stage (Atlas V rockets usually do not have a third stage). Previous flights had used none, two, or three solid boosters, but never five. This puts the Atlas V 551 take-off thrust, at well over 2,000,000 lbf (9 MN), past the Delta IV-Heavy. The major part of this thrust is supplied by the Russian RD-180 engine, providing 4.152 MN (933,000 lbf). The Delta IV-H remains the larger vehicle, at over 1,600,000 lb (726,000 kg) compared to 1,260,000 lb (572,000 kg) of the AV-010. The Atlas V rocket had earlier been slightly damaged when Hurricane Wilma swept across Florida on October 24, 2005. One of the solid rocket boosters was hit by a door. The booster was replaced with an identical unit, rather than inspecting and requalifying the original.

The Star 48B third stage is also on a hyperbolic solar system escape trajectory, and reached Jupiter before the *New Horizons* spacecraft. So did two small de-spin masses, the "yo-yo masses", released from the stage. However, since they are not in controlled flight, they did not receive the correct gravity assist, and will only pass within 200,000,000 km (120,000,000 mi) of Pluto.

New Horizons is often erroneously given the title of *Fastest Spacecraft Ever Launched*, when in fact the Helios probes are the holders of that title. To be more specific *New Horizons* achieved the highest launch velocity and thus left Earth faster than any other spacecraft to date. It is also the first spacecraft launched directly into a solar escape trajectory, which requires an approximate velocity of 16.5 km/s (36,900 mph), plus losses, all to be provided by the launcher. However, it will not be the fastest spacecraft to leave the solar system. This record is held by *Voyager 1*, currently travelling at 17.145 km/s (38,400 mph) relative to the Sun. *Voyager 1* attained greater hyperbolic excess velocity from Jupiter and Saturn gravitational slingshots than *New Horizons*. Other spacecraft, such as *Helios 1 & 2*, can also be measured as the fastest objects, due to their orbital velocity relative to the Sun at perihelion. However, because they remain in solar orbit, their orbital energy relative to the Sun is lower than the five probes, and three other third stages on hyperbolic trajectories, including *New Horizons*, that achieved solar escape velocity, as the Sun has a much deeper gravitational well than Earth.

Trajectory corrections and instrument testing

On January 28 and January 30, 2006, mission controllers guided the probe through its first trajectory correction maneuver (TCM), which was divided into two parts (TCM-1A and TCM-1B). The total velocity change of these two corrections was about 18 meters per second. TCM-1 was accurate enough to permit the cancellation of TCM-2, the second of three originally scheduled corrections.

During the week of February 20, controllers conducted initial in-flight tests of three onboard scientific instruments, the Alice ultraviolet imaging spectrometer, the PEPSSI plasma-sensor, and the LORRI long-range visible-spectrum camera. No scientific measurements or images were taken, but instrument electronics, and in the case of Alice, some electromechanical systems were shown to be functioning correctly.

On March 9 at 1700 UTC, controllers performed TCM-3, the last of three scheduled course corrections. The engines burned for 76 seconds, adjusting the spacecraft's velocity by about 1.16 meters per second.

On June 30, 2010 on 7:49 EDT, mission controllers executed a fourth TCM on *New Horizons* that lasted 35.6 seconds.

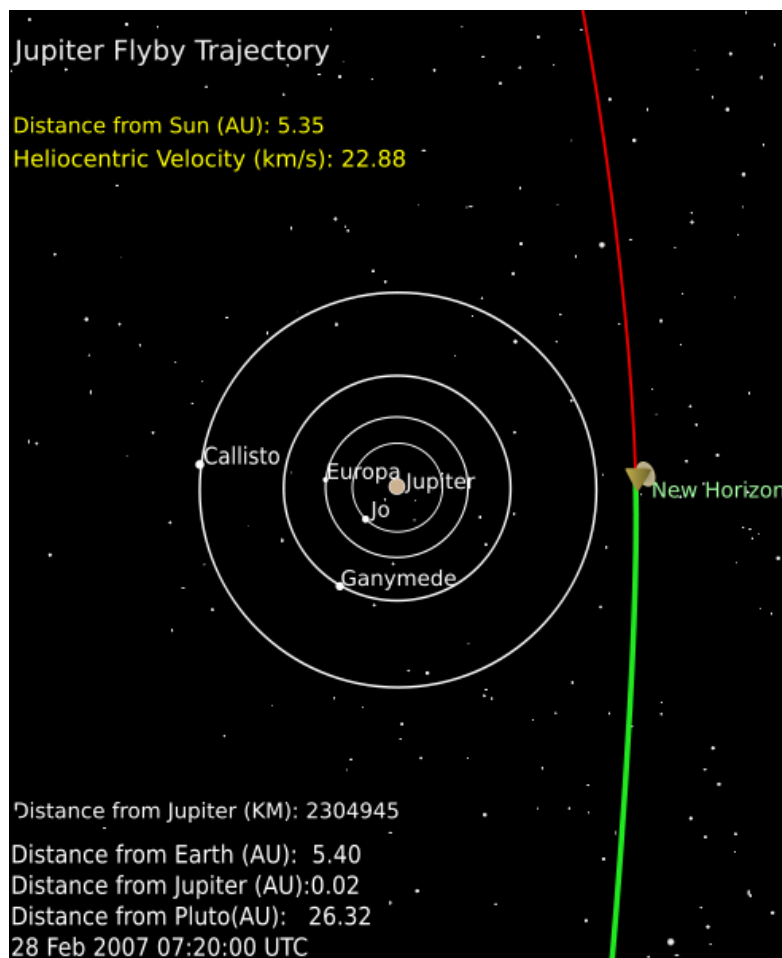
Passing Mars orbit and asteroid flyby

On April 7, 2006 at 10:00 UTC, the spacecraft passed the orbit of Mars, moving at roughly 21 km/s away from the Sun at a solar distance of 243 million kilometers.

New Horizons made a distant flyby of the small asteroid 132524 APL (previously known by its provisional designation, 2002 JF₅₆), at a distance of 101,867 km at 04:05 UTC on June 13, 2006. The best current estimate of the asteroid's diameter is approximately 2.3 kilometers, and the spectra obtained by *New Horizons* showed that APL is an S-type asteroid.

The spacecraft successfully tracked the asteroid over June 10 – June 12, 2006. This allowed the mission team to test the spacecraft's ability to track rapidly moving objects. Images were obtained through the Ralph telescope.

Jupiter gravity assist



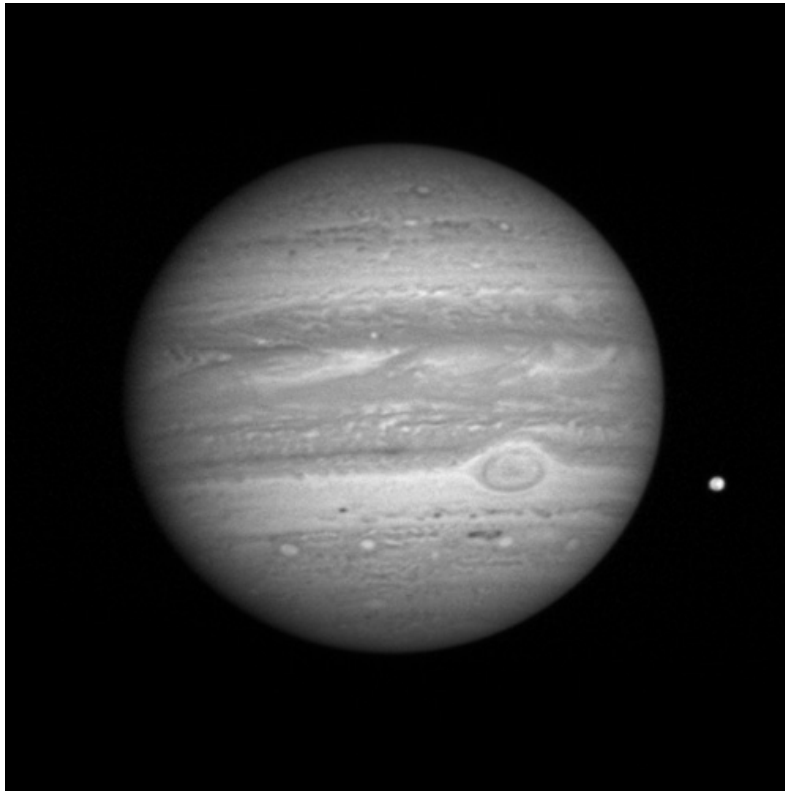
New Horizons at periapsis with Jupiter on February 28, 2007

New Horizons' Long Range Reconnaissance Imager (LORRI) took its first photographs of Jupiter on September 4, 2006. The spacecraft began further study of the Jovian system in December 2006.

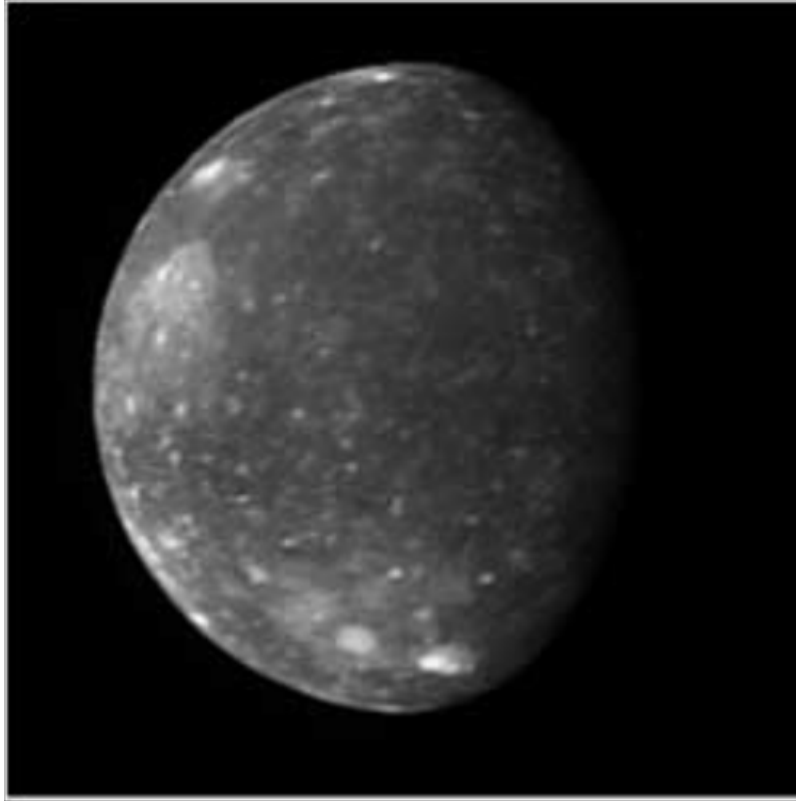
New Horizons received a Jupiter gravity assist with a closest approach at 5:43:40 UTC (12:43:40am EST) on February 28, 2007. It passed through the Jupiter system at 21 km/s (47,000 mph) relative to Jupiter (23 km/s (51,000 mph) relative to the Sun). The flyby increased *New Horizons'* speed away from the Sun by nearly 4 km/s (8,900 mph), putting the spacecraft on a faster trajectory to Pluto, about 2.5 degrees out of the plane of the Earth's orbit (the "ecliptic"). As of November, 2009, the gravitational attraction of the Sun has slowed down the spacecraft to about 16.656 km/s (37,260 mph). *New Horizons* was the first probe launched directly toward Jupiter since the *Ulysses* probe in 1990.

While at Jupiter, *New Horizons'* instruments made refined measurements of the orbits of Jupiter's inner moons, particularly Amalthea. The probe's cameras measured volcanoes on Io and studied all four Galilean moons in detail, as well as long distance studies of the outer moons Himalia and Elara. Imaging of the Jovian system began on September 4, 2006. The craft also studied Jupiter's Little Red Spot and the planet's magnetosphere and tenuous ring system.

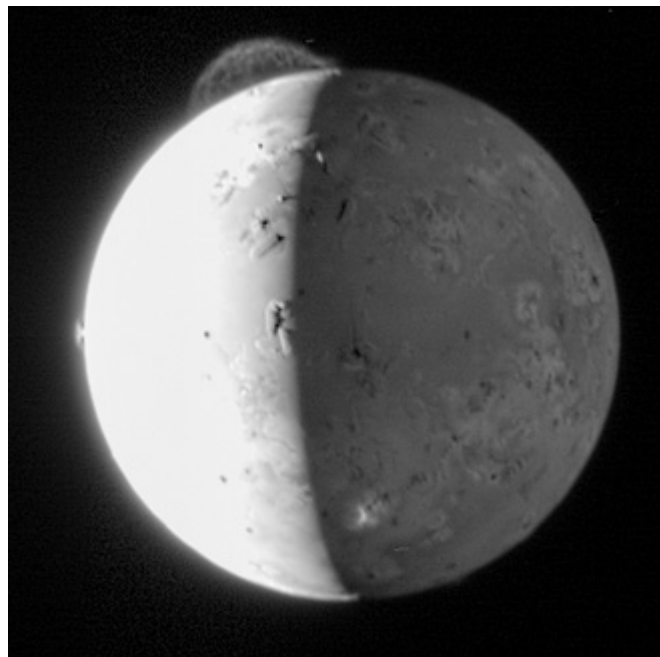
Jovian system imaged by *New Horizons*



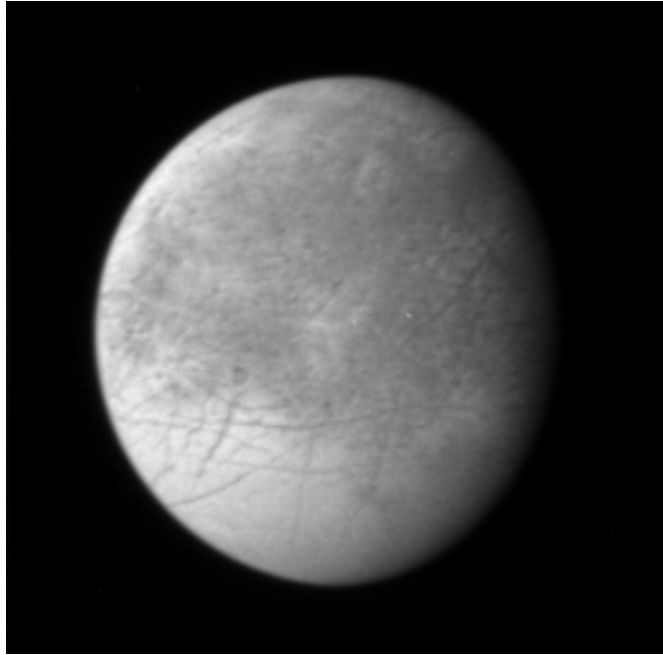
Jupiter and its moon Io imaged by *New Horizons* during flyby



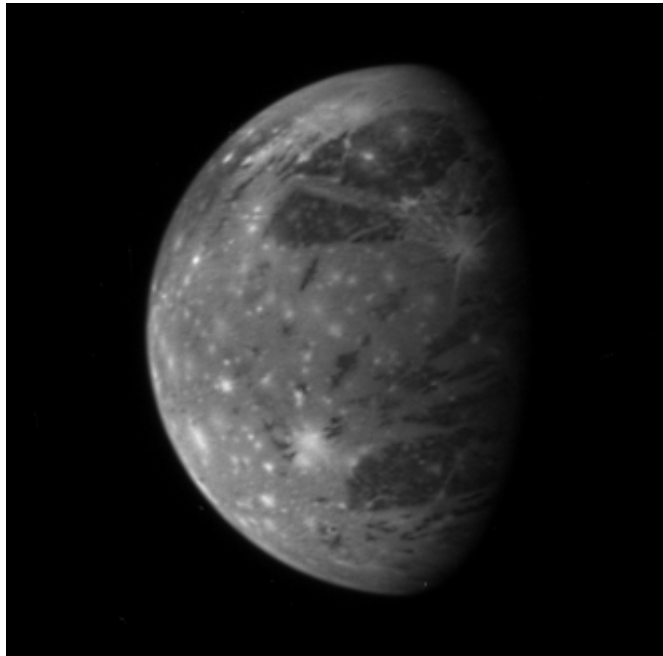
Callisto imaged by *New Horizons* during flyby



Io imaged by *New Horizons* during flyby

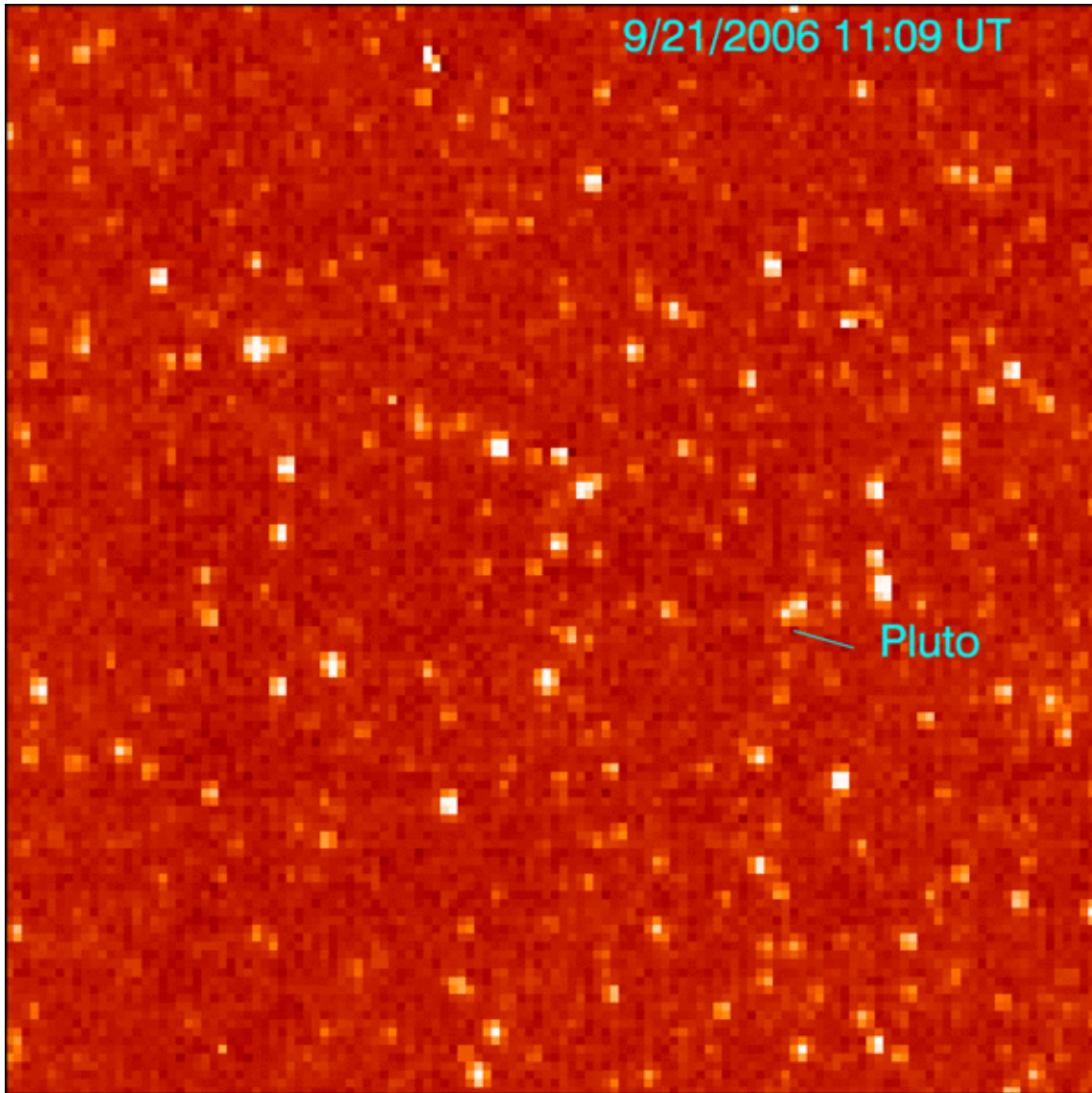


Europa imaged by *New Horizons* during flyby



Ganymede imaged by *New Horizons* during flyby

Pluto approach



First Pluto sighting from *New Horizons* (September 21–24, 2006)

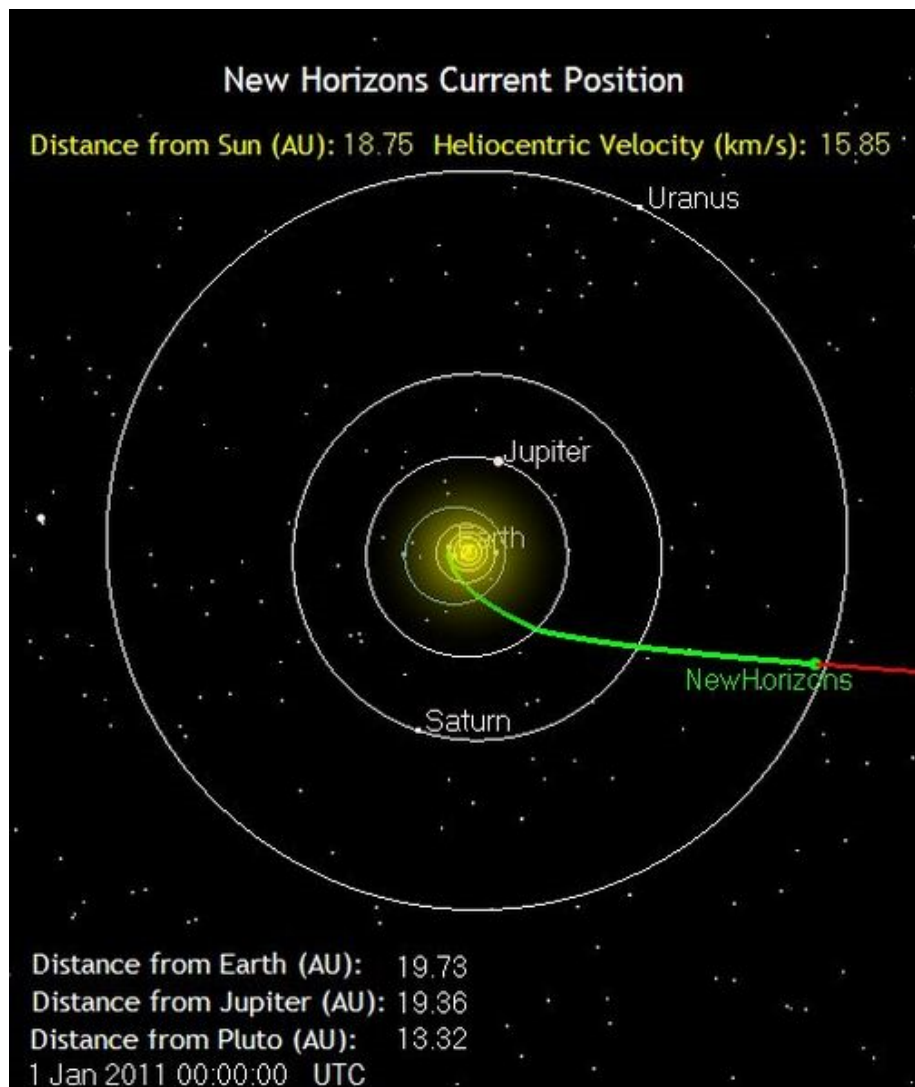
The first images of Pluto from *New Horizons* were created between September 21–24, 2006, during a test of the LORRI. They were released on November 28. The images, taken from a distance of approximately 4.2 billion kilometers (2.6 billion miles), confirmed the spacecraft's ability to track distant targets, critical for maneuvering toward Pluto and other Kuiper belt objects.

It is planned for *New Horizons* to fly within 10,000 km (6,200 mi) of Pluto in 2015. *New Horizons* will have a relative velocity of 13.78 km/s at closest approach, and will come as close as 27,000 km (17,000 mi) to Charon, although these parameters may be changed during flight.

Kuiper belt mission

After passing by Pluto, *New Horizons* will continue further into the Kuiper belt. Mission planners are now searching for one or more additional Kuiper belt objects (KBOs) on the order of 50–100 km (31–62 mi) in diameter for flybys similar to the spacecraft's Plutonian encounter. As maneuvering capability is limited, this phase of the mission is contingent on finding suitable KBOs close to *New Horizons*'s flight path, ruling out any possibility for a planned flyby of Eris, a trans-Neptunian object comparable in size to Pluto. The available region, being fairly close to the plane of the Milky Way and thus difficult to survey for dim objects, is one that has not been well-covered by previous KBO search efforts.

Key mission dates



Position of *New Horizons* (as of January 1st, 2011, 0h UTC)

- June 8, 2001 — New Horizons picked by NASA over a competing design, POSSE (Pluto and Outer Solar System Explorer).
- June 13, 2005 — Spacecraft departed APL for final testing at Goddard Space Flight Center (GSFC).
- September 24, 2005 — Spacecraft shipped to Cape Canaveral, through Andrews Air Force Base, aboard a C-17 Globemaster III cargo aircraft.
- December 17, 2005 — Transported from Hazardous Servicing Facility to Vertical Integration Facility at Space Launch Complex 41.
- January 11, 2006 — Primary launch window opened. Launch delayed for further testing.
- January 16, 2006 — Atlas V launcher, serial number AV-010, rolled out onto pad.
- January 17, 2006 — First day launch attempts scrubbed because of unacceptable weather conditions (high winds).
- January 18, 2006 — Second launch attempt scrubbed because of morning power outage at the Applied Physics Laboratory.
- January 19, 2006 — **Successful launch** at 14:00 EST (19:00 UTC) after brief delay due to cloud cover.
- April 7, 2006 — The probe passed Mars' orbit.
- Early May, 2006 — The probe entered the asteroid belt.
- June 13, 2006 — The probe passed closest to the asteroid 132524 APL in the Belt at about 101,867 km at 04:05 UTC. Pictures were taken.
- Late October, 2006 — The probe left the asteroid belt.
- November 28, 2006 — First faint image of Pluto taken from a distance released.
- January 8, 2007 — Start of Jupiter encounter.
- January 10, 2007 — Long distance observations of outer moon Callirrhoe as a navigation exercise.
- February 28, 2007 — Jupiter flyby. Closest approach occurred at 05:43:40 UTC at 2.305 million km, 21.219 km/s.
- March 5, 2007 — End of Jupiter encounter phase.
- June 8, 2008 — The probe passed Saturn's orbit.
- December 29, 2009 — The probe became closer to Pluto than to Earth
- March 8, 2010 - Distant flyby of 83982 Crantor
- October 17, 2010 — As of 4.25 UTC, half the mission time between launch and closest approach had elapsed, with 1731 days, 8 hours and 25 minutes remaining to closest approach and having elapsed since launch.

Planned

- March 18, 2011 — The probe will pass Uranus' orbit.
- August 24, 2014 — The probe will pass Neptune's orbit.
- July 14, 2015 — Flyby of Pluto around 11:47 UTC at 13,695 km, 13.78 km/s.
- July 14, 2015 — Flyby of Charon, Hydra and Nix around 12:01 UTC at 29,473 km, 13.87 km/s.
- 2016-2020 — Possible flyby of one or more Kuiper belt objects (KBOs).
- 2029 — The probe will leave the solar system.

Spacecraft subsystems

The spacecraft is comparable in size and general shape to a grand piano and has been compared to a "piano glued to a sports-car-sized satellite dish". As a point of departure, the team took inspiration from the Ulysses spacecraft, which also carried an RTG and dish on a box-in-box structure through the outer Solar System. Many subsystems and components have flight heritage from APL's CONTOUR spacecraft, which in turn had heritage from APL's TIMED spacecraft.

Structural

The spacecraft's body forms a triangle, almost 2.5 feet (0.76 m) thick. (The *Pioneers* had hexagonal bodies, while the *Voyagers*, *Galileo*, and *Cassini-Huygens* had decagonal, hollow bodies.) A 7075 aluminium alloy tube forms the main structural column, between the launch vehicle adapter ring at the "rear," and the 2.1 m radio dish antenna affixed to the "front" flat side. The titanium fuel tank is in this tube. The radioisotope thermoelectric generator, or RTG attaches with a 4-sided titanium mount resembling a grey pyramid or stepstool. Titanium provides strength and thermal isolation. The rest of the triangle is primarily sandwich panels of thin aluminum facesheet (less than $\frac{1}{64}$ in or 0.40 mm) bonded to aluminum honeycomb core.



New Horizons in its assembly hall

The structure is larger than strictly necessary, with empty space inside. The structure is designed to act as shielding, reducing electronics errors caused by radiation from the RTG. Also, the mass distribution required for a spinning spacecraft demands a wider triangle.

Propulsion and attitude control

New Horizons has both spin-stabilized (cruise) and three-axis stabilized (science) modes, controlled entirely with hydrazine monopropellant. 77 kg (170 lb) of hydrazine provides a delta-v capability of over 290 m/s (649 mph) after launch. Helium is used as a pressurant, with an elastomeric diaphragm assisting expulsion. The spacecraft's on-orbit mass including fuel will be over 470 kg (1,036 lb) for a Jupiter flyby trajectory, but would have been only 445 kg (981 lb) for a direct flight to Pluto. This would have meant less fuel for later Kuiper belt operations and is caused by the launch vehicle performance limitations for a direct-to-Pluto flight.

There are 16 thrusters on *New Horizons*: four 4.4 N (1.0 lbf) and twelve 0.9 N (0.2 lbf) plumbed into redundant branches. The larger thrusters are used primarily for trajectory corrections, and the small ones (previously used on *Cassini* and the *Voyager* spacecraft) are used primarily for attitude control and spinup/spindown maneuvers. Two star cameras (from Galileo Avionica) are used for fine attitude control. They are mounted on the face of the spacecraft and provide attitude information while in spinning or in 3-axis mode. Between star camera readings, knowledge is provided by dual redundant Miniature Inertial Measurement Unit (MIMU) from Honeywell. Each unit contains three solid-state gyroscopes and three accelerometers. Two Adcole Sun sensors provide coarse attitude control. One detects angle to the Sun, while the other measures spin rate and clocking.

Power

A cylindrical radioisotope thermoelectric generator, or RTG, protrudes from one vertex in the plane of the triangle. The RTG will provide about 240 W, 30 V DC at launch, and is predicted to drop approximately 5% every 4 years, decaying to 200 W by the encounter with the Plutonian system in 2015. The RTG, model "GPHS-RTG," was originally a spare from the Cassini mission. The RTG contains 11 kg (24 lb) of plutonium-238 oxide pellets. Each pellet is clad in iridium, then encased in a graphite shell. It was developed by the U.S. Department of Energy.

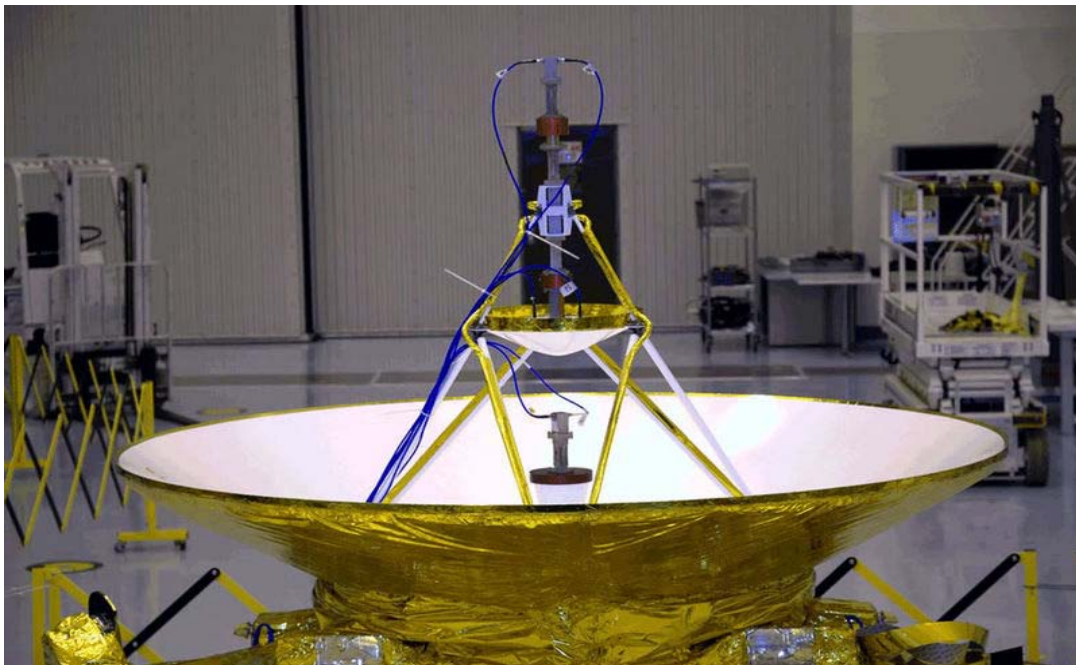
The use of a plutonium RTG battery resulted in minor demonstrations some days before launch by about 30 anti-nuclear protesters. The amount of radioactive plutonium in the RTG is 10.9 kg, about one-third the amount on-board the Cassini-Huygens probe when it launched in 1997. That launch was protested by over 300 people. The United States Department of Energy estimated the chances of a launch accident that would release radiation into the atmosphere at 1 in 350 and monitored the launch as it always does when RTGs are involved. It was believed that a worst-case scenario of total dispersal of on-board plutonium would spread the equivalent radiation of 80% the average annual dosage in North America from background radiation over an area with a radius of

65 miles (105 km), with cleanup costing anywhere from \$241 million – \$1.2 billion USD per square mile. at the Materials and Fuels Complex (formerly Argonne West), a part of the Idaho National Laboratory in Bingham County, near the town of Arco and the city of Idaho Falls. The plutonium was produced at Los Alamos National Laboratory in New Mexico. Less than the original design goal was produced, due to delays at the United States Department of Energy, including security activities, which held up production. The mission parameters and observation sequence had to be modified for the reduced wattage; still, not all instruments can operate simultaneously. The Department of Energy transferred the space battery program from Ohio to Argonne in 2002 because of security concerns. There are no onboard batteries. RTG output is relatively predictable; load transients are handled by a capacitor bank and fast circuit breakers.

Thermal

Internally, the structure is painted black. This equalizes temperature by radiative heat transfer. Overall, the spacecraft is thoroughly blanketed to retain heat. Unlike the Pioneers and Voyagers, the radio dish is also enclosed in blankets which extend to the body. The heat from the RTG also adds warmth to the spacecraft in the outer solar system. In the inner solar system, the spacecraft must prevent overheating. Electronic activity is limited, power is diverted to shunts with attached radiators, and louvers are opened to radiate excess heat. Then, when the spacecraft is cruising inactively in the cold outer solar system, the louvers are closed, and the shunt regulator reroutes power to electric heaters.

Telecommunications



Antennas of *New Horizons* (HGA, MGA and LGA)

Communication with the spacecraft is via X band.

At Pluto's distance a rate of approximately 1,000 bits per second is expected. The craft had a communication rate of 38 kbit/s at Jupiter.

The 70 m Deep Space Network (DSN) dishes will be used to relay data beyond Jupiter.

Besides the low bandwidth, Pluto's distance also causes a (one way) latency of about 4.5 hours.

The spacecraft uses dual redundant transmitters and receivers, and either right- or left-hand circular polarization. The downlink signal is amplified by dual redundant 12-watt TWTAs (traveling-wave tube amplifiers) mounted on the body under the dish.

The receivers are new, low-power designs. The system can be controlled to power both TWTAs at the same time, and transmit a dual-polarized downlink signal to the DSN that could almost double the downlink rate. Initial tests with the DSN in this dual-polarized mode have been successful, and an effort to make the DSN polarization-combining technique operational is underway.

In addition to the high-gain antenna, there are two low-gain antennas and a medium-gain dish. The high-gain dish has a Cassegrain layout, composite construction, and a 2.1 meter diameter (providing well over 40 dB of gain, and a half-power beam width of about a degree). The prime-focus, medium-gain antenna, with a 0.3 meter aperture and 10-degree half-power beamwidth, is mounted to the back of the high-gain antenna's secondary reflector. The forward low-gain antenna is stacked atop the feed of the medium-gain antenna. The aft low-gain antenna is mounted within the launch adapter at the rear of the spacecraft. This antenna was only used for early mission phases near Earth, just after launch and for emergencies if the spacecraft had lost attitude control.

To save mission costs, the spacecraft will be in "hibernation" between Jupiter and Pluto. It will awaken once per year, for 50 days, for equipment checkout and trajectory tracking. The rest of the time, the spacecraft will be in a slow spin, sending a beacon tone which will be checked once per week. Depending on frequency, the beacon indicates normal operation, or one of seven fault modes. *New Horizons* is the first mission to use the DSN's beacon tone system operationally, the system having been flight-tested by the DS1 mission.

Data handling

New Horizons will record scientific instrument data to its solid-state buffer at each encounter, then transmit the data to Earth. Data storage is done on two low-power solid-state recorders (one primary, one backup) holding up to 8 gigabytes each. Because of the extreme distance from Pluto and the Kuiper belt, only one buffer load at those encounters can be saved. This is because *New Horizons* will have left the vicinity of Pluto (or future target object) by the time it takes to transmit the buffer load back to Earth.

Part of the reason for the delay between the gathering and transmission of data is because all of the *New Horizons* instrumentation is body-mounted. In order for the cameras to record data, the entire probe must turn, and the one-degree-wide beam of the high-gain antenna will almost certainly not be pointing toward Earth. Previous spacecraft, such as the Voyager program probes, had a rotatable instrumentation platform (a "scan platform") that could take measurements from virtually any angle without losing radio contact with Earth. *New Horizons'* elimination of excess mechanisms was implemented to save weight, shorten the schedule, and improve reliability to achieve a 15+-year lifetime.

(The *Voyager 2* spacecraft experienced platform jamming at Saturn; the demands of long time exposures at Uranus led to modifications of the probe to rotate the entire probe instead to achieve the time exposure photos at Uranus and Neptune, similar to how *New Horizons* will rotate.)

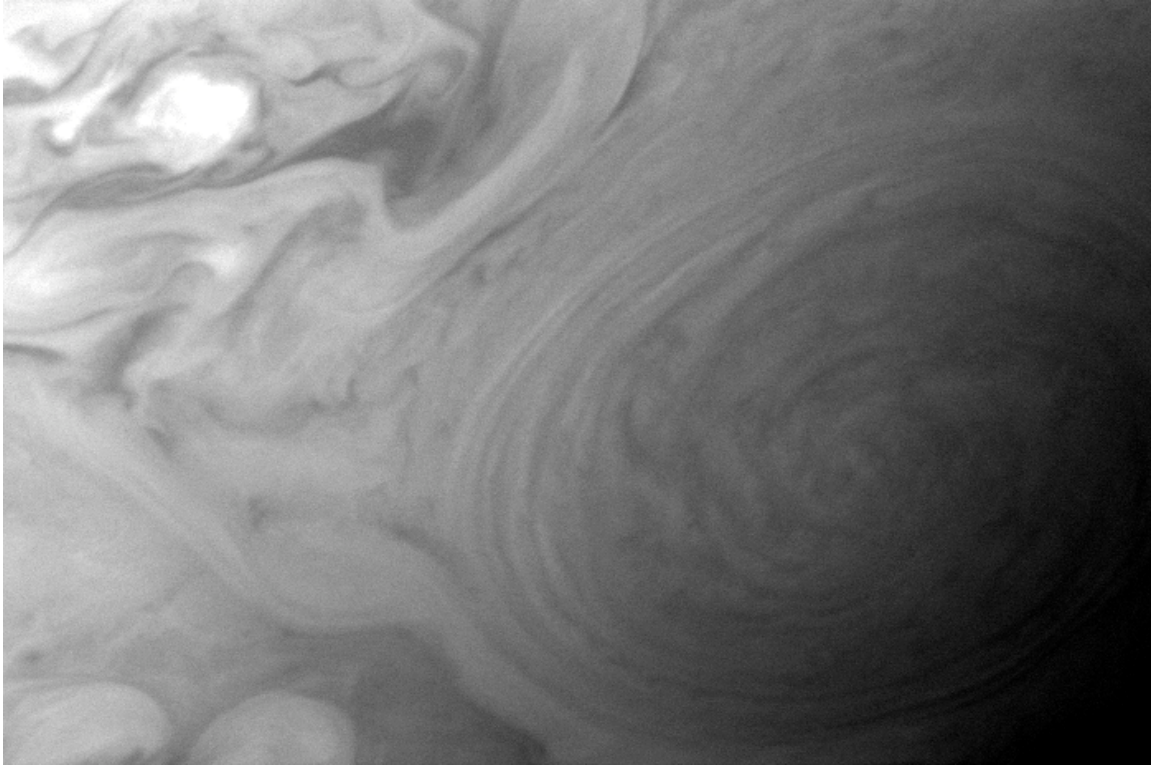
Flight computer

The spacecraft carries two computer systems, the Command and Data Handling system and the Guidance and Control processor. Each of the two systems is duplicated for redundancy, giving a total of four computers. The processor used is the Mongoose-V, a 12 MHz radiation-hardened version of the MIPS R3000 CPU. Multiple clocks and timing routines are implemented in hardware and software to help prevent faults and downtime.

To conserve heat and mass, spacecraft and instrument electronics are housed together in IEMs (Integrated Electronics Modules). There are two redundant IEMs. Including other functions such as instrument and radio electronics, each IEM contains 9 boards.

On March 19, 2007 the Command and Data Handling computer experienced an uncorrectable memory error and rebooted itself, causing the spacecraft to go into safe mode. The craft fully recovered within two days, with some data loss on Jupiter's magnetotail. No impact on the subsequent mission is expected.

Mission science



Enhanced view of Jupiter's "Little Red Spot" by the *New Horizons* space probe

The spacecraft carries seven scientific instruments. Total mass is 31 kg; rated power is 21 watts (though not all instruments operate simultaneously).

Long Range Reconnaissance Imager (LORRI)

A visible-light, high-resolution CCD imager with a 208.3 mm (8.20 in) aperture and 1024×1024 monochromatic CCD. Resolution is 5 microradians (approximately one arcsecond). The CCD is chilled far below freezing by a passive radiator on the antisolar face of the spacecraft. This temperature differential requires insulation, and isolation from the rest of the structure. The Ritchey-Chretien mirrors and metering structure are made of silicon carbide, to boost stiffness, reduce weight, and prevent warping at low temperatures. The optical elements sit in a composite light shield, and mount with titanium and fiberglass for thermal isolation. Overall mass is 8.6 kg, with the Optical tube assembly (OTA) weighing about 5.6 kg, for one of the largest silicon-carbide telescopes yet flown.

Pluto Exploration Remote Sensing Investigation (PERSI)

This consists of two instruments: The **Ralph** telescope, 6 centimeters in aperture, with two separate channels: a visible-light CCD imager (MVIC- Multispectral Visible Imaging Camera) with broadband and color channels, and a near-infrared imaging spectrometer, LEISA (Linear Etalon Imaging Spectral Array). LEISA is

derived from a similar instrument on the EO-1 mission. The second instrument is an ultraviolet imaging spectrometer, **Alice**. Alice resolves 1,024 wavelength bands in the far and extreme ultraviolet (from 180 to 50 nanometers), over 32 view fields. Its goal is to view the atmospheric makeup of Pluto. This Alice is derived from an Alice on the Rosetta mission. Ralph, designed afterwards, was named after Alice's husband on *The Honeymooners*. Ralph and Alice are names, not acronyms.

Plasma and high energy particle spectrometer suite (PAM)

Two instruments, consisting of **SWAP** (Solar Wind At Pluto), a toroidal electrostatic analyzer and retarding potential analyzer, and **PEPSSI** (Pluto Energetic Particle Spectrometer Science Investigation), a time of flight ion and electron sensor. SWAP measures particles of up to 6.5 keV, PEPSSI goes up to 1 MeV. Because of the tenuous solar wind at Pluto's distance, the SWAP instrument has the largest aperture of any such instrument ever flown.

Radio Science Experiment (REX)

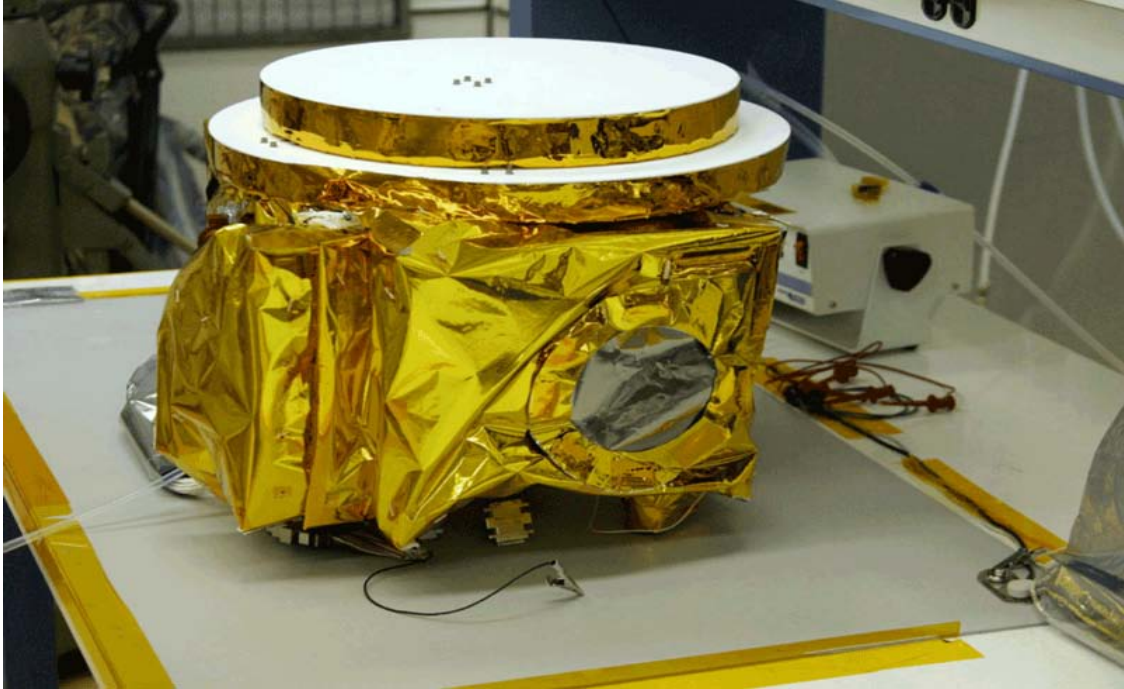
REX will use an ultrastable crystal oscillator (essentially a calibrated crystal in a miniature oven) and some additional electronics to conduct radio science investigations using the communications channels. These are small enough to fit on a single card. Since there are two redundant communications subsystems, there are two, identical REX circuit boards.



New Horizon's image of Jupiter's Himalia

Venetia Burney Student Dust Counter (VBSDC)

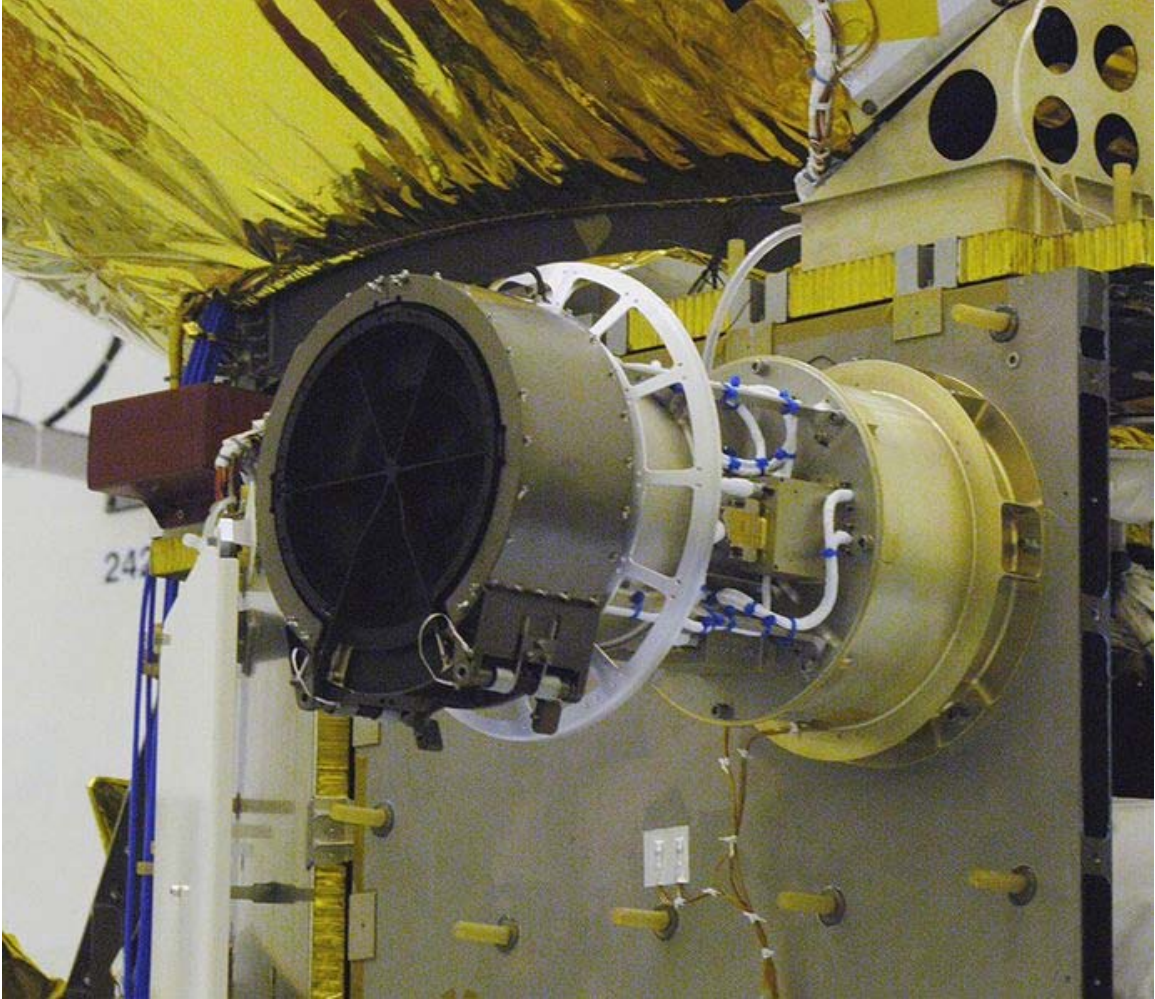
Built by students at the University of Colorado at Boulder, the **Student Dust Counter** will operate continuously through the trajectory to make dust measurements. It consists of a detector panel, about 18 by 12 inches (460 × 300 mm), mounted on the antisolar face of the spacecraft (the ram direction), and an electronics box within the spacecraft. The detector contains fourteen PVDF panels, twelve science and two reference, which generate voltage when impacted. Effective collecting area is 0.125 m². No dust counter has operated past the orbit of Uranus; models of dust in the outer solar system, especially the Kuiper belt, are speculative. VBSDC is always turned on measuring the masses of the interplanetary and interstellar dust particles (in the range of nano and pico grams) as they collide with the PVDF panels mounted on the New Horizons spacecraft. The measured data shall greatly contribute to our understanding of the dust spectra of our own solar system. We can then compare our dust spectra with those observed via telescope of other stars, and that would give us new clues as to where earth like planets can be found in our universe. The dust counter is named for Venetia Burney, who first suggested the name "Pluto" at the age of 11. An interesting thirteen minute short film about VBSDC garnered an Emmy award for student achievement in 2006.



Ralph



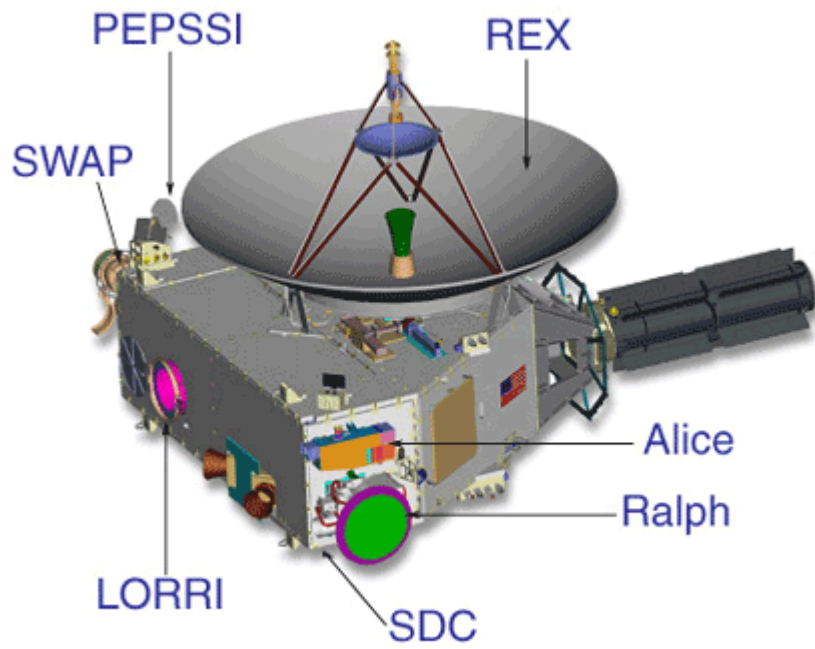
LORRI



SWAP

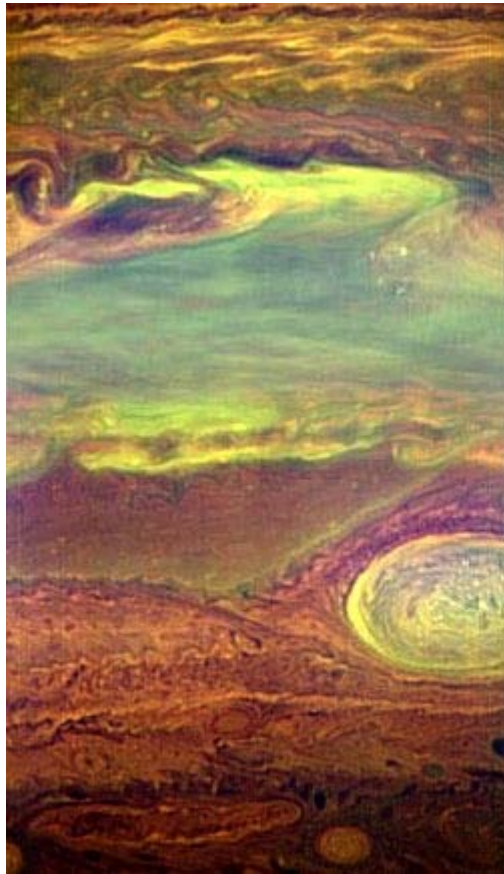


VBSDC



Instrument Locations

Jupiter observations



Jupiter through infrared camera

The flyby came within about 32 Jovian radii (3 Gm) of Jupiter and was the center of a 4-month intensive observation campaign. Jupiter is an interesting, ever-changing target, observed intermittently since the end of the Galileo mission. *New Horizons* also has instruments built using the latest technology, especially in the area of cameras. They are much improved over Galileo's cameras, which were evolved versions of Voyager cameras which, in turn, were evolved Mariner cameras. The Jupiter encounter also served as a shakedown and dress rehearsal for the Pluto encounter. Because of the much shorter distance from Jupiter to Earth, the communications link can transmit multiple loadings of the memory buffer. The mission will actually return more data from Jupiter than Pluto. Imaging of Jupiter began on September 4, 2006, after which several images were taken.

The primary encounter goals included Jovian cloud dynamics, which were greatly reduced from the Galileo observation program, and particle readings from the magnetotail of the Jovian magnetosphere. The spacecraft trajectory coincidentally flew down the magnetotail for months. *New Horizons* also examined the Jovian nightside for aurorae and lightning.

New Horizons also provided the first close-up examination of Oval BA, a storm feature that has informally become known as the "Little Red Spot", since the storm turned red. It was still a white spot when *Cassini* flew by.

Jovian moons

The major (Galilean) moons were in poor position. The aim point of the gravity-assist maneuver meant the spacecraft passed millions of kilometers from any of the Galilean moons. Still, the *New Horizons* instruments were intended for small, dim targets, so they were scientifically useful on large, distant moons. LORRI searched for volcanoes and plumes on Io. The infrared capabilities of LEISA searched for chemical compositions (including Europa ice dopants), and nightside temperatures (including hotspots on Io). The ultraviolet resolution of Alice searched for aurorae and atmospheres, including the Io torus.

Minor moons such as Amalthea had their orbit solutions refined. The cameras determined their position, acting as "reverse optical navigation".

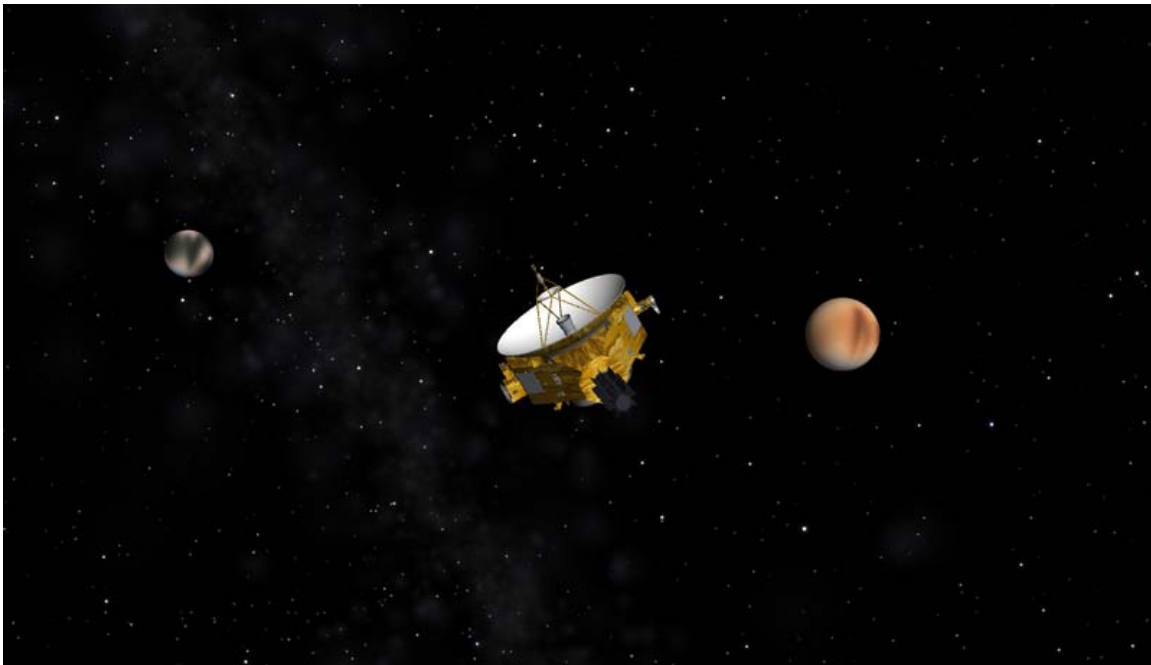
Pluto flyby



Computer-generated view from the spacecraft during flyby of Pluto (right) showing its moon, Charon (left).

Observations of Pluto, with LORRI plus Ralph, will begin about 6 months prior to closest approach. The targets will be only a few pixels across. This should detect any rings or any additional moons (eventually down to 2 kilometers diameter), for avoidance and targeting maneuvers, and observation scheduling. 70 days out, resolution will exceed the Hubble Space Telescope's resolution, lasting another two weeks after the flyby. Long-range imaging will include 40 km (25 mi) mapping of Pluto and Charon 3.2 days out. This is half the rotation period of Pluto-Charon and will allow imaging of the side of both bodies that will be facing away from the spacecraft at closest approach. Coverage will repeat twice per day, to search for changes due to snows or cryovolcanism. Still, due to Pluto's tilt and rotation, a portion of the northern hemisphere will be in shadow at all times.

During the flyby, LORRI should be able to obtain select images with resolution as high as 50 m/px (if closest distance is around 10,000 km), and MVIC should obtain 4-color global dayside maps at 1.6 km resolution. LORRI and MVIC will attempt to overlap their respective coverage areas to form stereo pairs. LEISA will obtain hyperspectral near-infrared maps at 7 km/px globally and 0.6 km/pixel for selected areas. Meanwhile, Alice will characterize the atmosphere, both by emissions of atmospheric molecules (airglow), and by dimming of background stars as they pass behind Pluto (occultation).



A simulated view of New Horizons passing Pluto and Charon when it arrives in 2015

During and after closest approach, SWAP and PEPSSI will sample the high atmosphere and its effects on the solar wind. VBSDC will search for dust, inferring meteoroid collision rates and any invisible rings. REX will perform active and passive radio science. Ground stations on Earth will transmit a powerful radio signal as *New Horizons* passes behind Pluto's disk, then emerges on the other side. The communications dish will

measure the disappearance and reappearance of the signal. The results will resolve Pluto's diameter (by their timing) and atmospheric density and composition (by their weakening and strengthening pattern). (Alice can perform similar occultations, using sunlight instead of radio beacons.) Previous missions had the spacecraft transmit through the atmosphere, to Earth ("downlink"). Low power and extreme distance means New Horizons will be the first such "uplink" mission. Pluto's mass and mass distribution will be evaluated by their tug on the spacecraft. As the spacecraft speeds up and slows down, the radio signal will experience a Doppler shift. The Doppler shift will be measured by comparison with the ultrastable oscillator in the communications electronics.

Reflected sunlight from Charon will allow some imaging observations of the nightside. Backlighting by the Sun will highlight any rings or atmospheric hazes. REX will perform radiometry of the nightside.

Initial, highly-compressed images will be transmitted within days. The science team will select the best images for public release. Uncompressed images will take about nine months to transmit, depending on Deep Space Network traffic. It may turn out, however, that fewer months will be needed. The spacecraft link is proving stronger than expected, and it is possible that both downlink channels may be ganged together to nearly double the data rate.

Primary objectives (required)

- Characterize the global geology and morphology of Pluto and Charon
- Map chemical compositions of Pluto and Charon surfaces
- Characterize the neutral (non-ionized) atmosphere of Pluto and its escape rate

Loss of any of these objectives will constitute a failure of the mission.

Secondary objectives (expected)

- Characterize the time variability of Pluto's surface and atmosphere
- Image select Pluto and Charon areas in stereo
- Map the terminators (day/night border) of Pluto and Charon with high resolution
- Map the chemical compositions of select Pluto and Charon areas with high resolution
- Characterize Pluto's ionosphere, and its interaction with the solar wind
- Search for neutral species such as H₂, hydrocarbons, HCN and other nitriles in the atmosphere
- Search for any Charon atmosphere
- Determine bolometric bond albedos for Pluto and Charon
- Map surface temperatures of Pluto and Charon

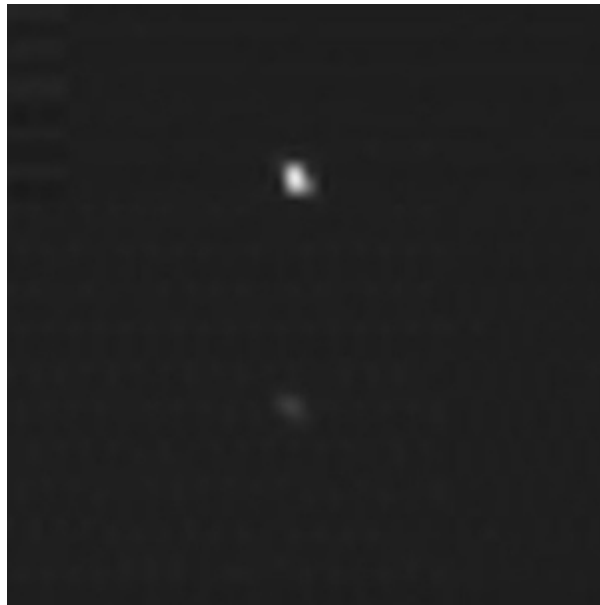
It is expected, but not demanded, that most of these objectives will be met.

Tertiary objectives (desired)

- Characterize the energetic particle environment at Pluto and Charon
- Refine bulk parameters (radii, masses) and orbits of Pluto and Charon
- Search for additional moons, and any rings

These objectives may be attempted, though they may be skipped in favor of the above objectives. An objective to measure any magnetic field of Pluto was dropped. A magnetometer instrument could not be implemented within a reasonable mass budget and schedule, and SWAP and PEPSSI could do an indirect job detecting some magnetic field around Pluto.

Asteroid belt



The 2.5 kilometer-wide asteroid 132524 APL, photographed by the *New Horizons* probe

Because of the need to conserve fuel for possible encounters with Kuiper belt objects subsequent to the Pluto flyby, intentional encounters with objects in the asteroid belt were not planned. Subsequent to launch, the *New Horizons* team scanned the spacecraft's trajectory to determine if any asteroids would, by chance, be close enough for observation. In May 2006 it was discovered that *New Horizons* would pass close to the tiny asteroid 132524 APL on June 13, 2006. Closest approach occurred at 4:05 UTC at a distance of 101,867 kilometers. The asteroid was imaged by Ralph (use of LORRI at that time was not possible due to proximity to sun), which gave the team a chance to exercise Ralph's capabilities, and make observations of the asteroid's composition as well as light and phase curves. The asteroid was estimated to be 2.5 kilometers in diameter.

Neptune trojans

Other possible targets are Neptune trojans. The probe's trajectory to Pluto passes near Neptune's trailing Lagrange point ("L₅"), which may host hundreds of bodies in 1:1

resonance with the planet (the first one, 2008 LC₁₈, was discovered in 2008). If any Neptune trojans are found to be close enough to be studied, observations may be planned. However, spacecraft passage near this Lagrange point comes shortly before the Pluto encounter. Depending on where the object is along the spacecraft trajectory, *New Horizons* may not have significant downlink bandwidth, and thus free memory, for trojan encounter data.

Kuiper belt objects

New Horizons is designed to fly past one or more Kuiper belt objects (KBOs) after passing Pluto. Because the flight path is determined by the Pluto flyby, with only minimal hydrazine remaining, objects must be found within a cone, extending from Pluto, of less than a degree's width, within 55 AU. Past 55 AU, the communications link becomes too weak, and the RTG wattage will have decayed significantly enough to hinder observations. Desirable KBOs will be well over 50 km in diameter, neutral in color (to compare with the reddish Pluto), and, if possible, possess a moon. Because the population of KBOs appears quite large, multiple objects may qualify. Large ground telescopes, such as Pan-STARRS and later the Large Synoptic Survey Telescope, will find suitable objects up until the Pluto flyby; the Pluto aim point, plus some thruster firing, will then determine the subsequent trajectory. KBO flyby observations will be similar to those at Pluto, but reduced due to lower light, power, and bandwidth.

Heliosphere

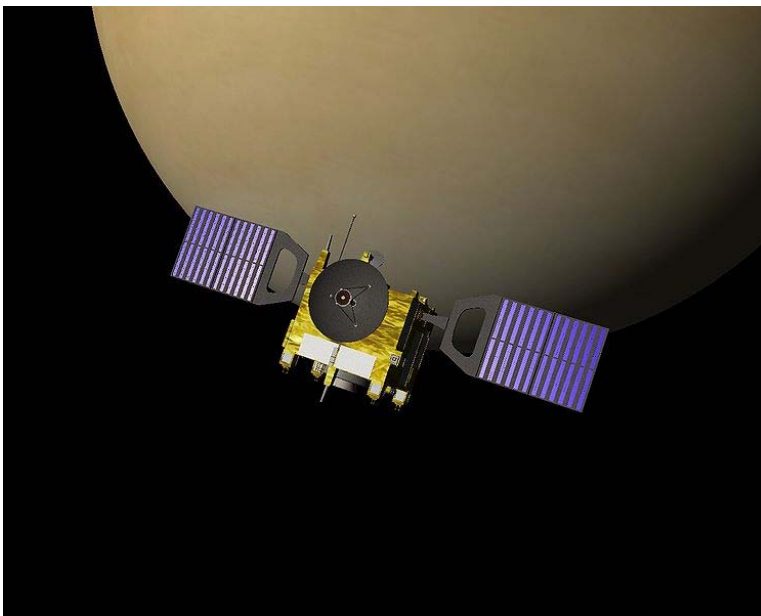
Provided it survives that far out, *New Horizons* is likely to follow the Voyager probes in exploring the outer heliosphere and mapping the heliosheath and heliopause.

Even though it was launched far faster than any outward probe before it, *New Horizons* will never overtake *Voyager 1* as the most distant man-made object from Earth. Close fly-bys of Saturn and Titan gave *Voyager 1* a massive advantage with its extra gravity assist. When *New Horizons* reaches the distance of 100 AU, it will be travelling at about 13 km/s, around 4 km/s slower than *Voyager 1* at that distance.

Chapter 8

Venus Express

Venus Express



Operator	ESA
Major contractors	EADS Astrium, Toulouse, France, leading a team of 25 subcontractors from 14 European countries.
Mission type	Orbiter
Satellite of	Venus
Launch date	9 November 2005 03:33:34 UTC
Launch vehicle	Soyuz-FG/Fregat
Mission duration	150 days enroute; 1,000 days in orbit 5 years, 2 months, and 4 days elapsed

COSPAR ID 2005-045A

Mass 1,270 kg

Orbital elements

Semimajor axis 39,468.195 km

Eccentricity 0.8403

Inclination 89.99 deg

Orbital period 24 h

Venus Express (VEX) is the first Venus exploration mission of the European Space Agency. Launched in November 2005, it arrived at Venus in April 2006 and has been continuously sending back science data from its polar orbit around Venus. Equipped with seven science instruments, the main objective of the mission is the long term observation of the Venusian atmosphere. The observation over such long periods of time has never been done in previous missions to Venus, and is key to a better understanding of the atmospheric dynamics. It is hoped that such studies can contribute to an understanding of atmospheric dynamics in general, while also contributing to an understanding of climate change on Earth. The mission is currently funded by ESA through 31 December 2012.

History

The mission was proposed in 2001 to reuse the design of the *Mars Express* mission. However, some mission characteristics led to design changes: primarily in the areas of thermal control, communications and electrical power. For example, since Mars is approximately twice as far from the Sun as Venus is, the radiant heating of the spacecraft will be four times greater for *Venus Express* than *Mars Express*. Also, the ionizing radiation environment will be harsher. On the other hand, the more intense illumination of the solar panels will result in more generated photovoltaic power. The *Venus Express* mission also uses some spare instruments developed for the *Rosetta* spacecraft. The mission was proposed by a consortium led by D. Titov (Germany), E. Lellouch (France) and F. Taylor (United Kingdom).

The launch window for *Venus Express* was open from 26 October to 23 November 2005, with the launch initially set for 26 October 4:43 UTC. However, problems with the insulation from the Fregat upper stage led to a two week launch delay to inspect and clear out the small insulation debris that migrated on the spacecraft. It was eventually launched by a Soyuz-FG/Fregat rocket from the Baikonur Cosmodrome in Kazakhstan on 9 November 2005 at 03:33:34 UTC into a parking Earth orbit and 1 h 36 min after launch put into its transfer orbit to Venus. A first trajectory correction maneuver was successfully performed on 11 November 2005. It arrived at Venus on 11 April 2006, after approximately 150 days of journey, and fired its main engine between 07:10 and 08:00 Universal Time (UTC) to reduce its velocity so that it could be captured by Venusian

gravity into a nine day orbit. The burn was monitored from ESA's Control Centre, ESOC, in Darmstadt, Germany.

Seven further orbit control maneuvers, two with the main engine and five with the thrusters, were required for *Venus Express* to reach its final operational 24-hour orbit around Venus.

Venus Express entered its target orbit at apocentre on 7 May 2006 at 13:31 UTC, when the spacecraft was at 151 million kilometres from Earth. Now the spacecraft is running on an ellipse substantially closer to the planet than during the initial orbit. The orbit now ranges between 66,000 and 250 kilometres over Venus and it is polar. The pericentre is located almost above the North pole (80° North latitude), and it takes 24 hours for the spacecraft to travel around the planet.

Venus Express is studying the Venusian atmosphere and clouds in detail, the plasma environment and the surface characteristics of Venus from orbit. It will also make global maps of the Venusian surface temperatures. Its nominal mission was originally planned to last for 500 Earth days (approximately two Venusian sidereal days), but the mission has been extended twice: first on 28 February 2007 until early May 2009; then on 4 February 2009 until 31 December 2009; and then on 7 October 2009 until 31 December 2012. On-board resources are sized for an additional 500 Earth days.

Venus Express is outfitted mostly with spare parts and designs from the *Mars Express* and *Rosetta* missions, but has been adapted to cope with the high radiation and thermal environment surrounding Venus.

Instruments

ASPERA-4: An acronym for "Analyzer of Space Plasmas and Energetic Atoms," ASPERA-4 will investigate the interaction between the solar wind and the Venusian atmosphere, determine the impact of plasma processes on the atmosphere, determine global distribution of plasma and neutral gas, study energetic neutral atoms, ions and electrons, and analyze other aspects of the near Venus environment. ASPERA-4 is a re-use of the ASPERA-3 design used on *Mars Express*, but adapted for the harsher near-Venus environment.

VMC: The Venus Monitoring Camera is a wide-angle, multi-channel CCD. The VMC is designed for global imaging of the planet. It operates in the visible, ultraviolet, and near infrared spectral ranges, and maps surface brightness distribution searching for volcanic activity, monitoring airglow, studying the distribution of unknown ultraviolet absorbing phenomenon at the cloud-tops, and making other science observations. It is derived in part by the *Mars Express* High Resolution Stereo Camera (HRSC) and the *Rosetta* Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS). The camera includes an FPGA to pre-process image data, reducing the amount transmitted to Earth. The consortium of institutions responsible for the VMC includes the Max Planck Institute for Solar System Research, the Institute of Planetary Research at the German Aerospace

Center and the Institute of Computer and Communication Network Engineering at Technische Universität Braunschweig.

Magnetometer

MAG: The magnetometer is designed to measure the strength of Venus's magnetic field and the direction of it as affected by the solar wind and Venus itself. It will be able to map the magnetosheath, magnetotail, ionosphere, and magnetic barrier in high resolution in three-dimensions, aid ASPERA-4 in the study of the interaction of the solar wind with the atmosphere of Venus, identify the boundaries between plasma regions, and carry planetary observations as well (such as for lightning). MAG is derived from the *Rosetta* lander's ROMAP instrument.

Spectrometer

PFS: The "Planetary Fourier Spectrometer" operates in the infrared between the 0.9 μm and 45 μm wavelength range and is designed to perform vertical optical sounding of the Venus atmosphere. It will perform global, long-term monitoring of the three-dimensional temperature field in the lower atmosphere (cloud level up to 100 kilometers).

Furthermore it will search for minor atmospheric constituents that may be present, but have not yet been detected, analyze atmospheric aerosols, and investigate surface to atmosphere exchange processes. The design is based on a spectrometer on *Mars Express*, but modified for optimal performance for the *Venus Express* mission.

SPICAV: Short for "Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus," SPICAV is an imaging spectrometer that will be used for analyzing radiation in the infrared and ultraviolet wavelengths. It is derived from the *SPICAM* instrument flown on *Mars Express*. However, SPICAV has an additional channel known as **SOIR** (Solar Occultation at Infrared) that will be used to observe the Sun through Venus's atmosphere in the infrared.

VIRTIS: VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) is an imaging spectrometer that observes in the near-ultraviolet, visible, and infrared parts of the electromagnetic spectrum. It will analyze all layers of the atmosphere, surface temperature and surface/atmosphere interaction phenomena.

Radio science

VeRa: Venus Radio Science is a radio sounding experiment that will transmit radio waves from the spacecraft and pass them through the atmosphere or reflect them off the surface. These radio waves will be received by a ground station on Earth for analysis of the ionosphere, atmosphere and surface of Venus. It is derived from the Radio Science Investigation instrument flown on *Rosetta*.

Science

Climate of Venus

Venus is the most Earth-like planet in our solar system. Starting out in the early planetary system with similar sizes and chemical compositions, the history of the two planets have diverged in spectacular fashion. It is hoped that the *Venus Express* mission can contribute not only to an in-depth understanding of how the Venusian atmosphere is structured, but also to an understanding of the changes that led to the current greenhouse atmospheric conditions. Such an understanding may contribute to the study of climate change in on Earth.

Search for life on Earth

Venus Express is used also to observe signs of life on Earth from Venus orbit. In the pictures, Earth is less than one pixel in size, which mimics observations of Earth-sized planets in other solar systems. These observations are then used to develop methods for habitability studies of extra-solar planets.

Important events and discoveries

- 3 August 2005: *Venus Express* completed its final phase of testing at Astrium Intespace facility in Toulouse, France. It flew on a Antonov An-124 cargo aircraft via Moscow, before arriving at Baikonur on 7 August.
- 7 August 2005: *Venus Express* arrived at the airport of the Baikonur Cosmodrome.
- 16 August 2005: First flight verification test completed.
- 22 August 2005: Integrated System Test-3.
- 30 August 2005: Last Major System Test Successfully Started.
- 5 September 2005: Electrical Testing Successful.
- 21 September 2005: FRR (Fuelling Readiness Review) Ongoing.
- 12 October 2005: Mating to the Fregat upper stage completed.
- 21 October 2005: Contamination detected inside the fairing — launch on hold.
- 5 November 2005: Arrival at launch pad.
- 9 November 2005: Launch from Baikonur Cosmodrome at 03:33:34 UTC.
- 11 November 2005: First trajectory correction maneuver successfully performed.
- 17 February 2006: The main engine is fired successfully in a dress rehearsal for the arrival maneuver.
- 24 February 2006: Second trajectory correction maneuver successfully performed.
- 29 March 2006: Third trajectory correction maneuver successfully performed - on target for 11 April orbit insertion.
- 7 April 2006: Command stack for orbit insertion maneuver is loaded on the spacecraft.
- 11 April 2006: The Venus Orbit Insertion (VOI) is completed successfully, according to the following timeline:

	spacecraft time (UTC)	ground receive time (UTC)
Liquid Settling Phase start	07:07:56	07:14:41
VOI main engine start	07:10:29	07:17:14
pericentre passage	07:36:35	
eclipse start	07:37:46	
occultation start	07:38:30	07:45:15
occultation end	07:48:29	07:55:14
eclipse end	07:55:11	
VOI burn end	08:00:42	08:07:28

Period of this orbit is nine days.

- 13 April 2006: First images of Venus from *Venus Express* released.
- 20 April 2006: Apocentre Lowering Manoeuvre #1 performed. Orbital period is now 40 hours.
- 23 April 2006: Apocentre Lowering Manoeuvre #2 performed. Orbital period is now approx 25 hours 43 minutes.
- 26 April 2006: Apocentre Lowering Manoeuvre #3 is slight fix to previous ALM.
- 7 May 2006: *Venus Express* entered its target orbit at apocentre at 13:31 UTC
- 14 December 2006: First temperature map of the southern hemisphere.
- 27 February 2007: ESA agrees to fund mission extension until May 2009.
- 19 September 2007: End of the nominal mission (500 Earth days) - Start of mission extension.
- 27 November 2007: The scientific journal *Nature* publishes a series of papers giving the initial findings. It finds evidence for past oceans. It confirms the presence of lightning on Venus and that it is more common on Venus than it is on Earth. It also reports the discovery that a huge double atmospheric vortex exists at the south pole of the planet.
- 20 May 2008: The detection by the VIRTIS instrument on *Venus Express* of hydroxyl (OH) in the atmosphere of Venus is reported in the May 2008 issue of *Astronomy and Astrophysics*.
- 4 February 2009: ESA agrees to fund mission extension until 31 December 2009.
- 7 October 2009: ESA agrees to fund the mission through 31 December 2012.

Chapter 9

Mars Reconnaissance Orbiter

Mars Reconnaissance Orbiter



Conceptual image depicting the Mars Reconnaissance Orbiter in an elliptical low-planet orbit around Mars

Operator	NASA / JPL Lockheed Martin Space Systems University of Arizona
Major contractors	Applied Physics Laboratory Italian Space Agency Malin Space Science Systems,
Mission type	Orbiter
Satellite of	Mars
Orbital insertion	2006-03-10 21:24:00 UTC

date

Launch date	2005-08-12 11:43:00 UTC
Carrier rocket	Atlas V-401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	Primary mission: >2 years elapsed: 5 years and 5 months
COSPAR ID	2005-029A
Mass	2,180 kilograms (4,800 lb) fueled 1,031 kilograms (2,270 lb) dry
Power	1,000.0 W

Mars Reconnaissance Orbiter (MRO) is a NASA multipurpose spacecraft designed to conduct reconnaissance and exploration of Mars from orbit. As MRO entered orbit it joined five other spacecraft in orbit of or on the planet including: *Mars Global Surveyor*, *Mars Express*, *Mars Odyssey*, and two *Mars Exploration Rovers*; a then record for most spacecraft operational in Mars vicinity. The US\$720 million spacecraft was built by Lockheed Martin under the supervision of the Jet Propulsion Laboratory. It was launched August 12, 2005, and attained Martian orbit on March 10, 2006. In November 2006, after five months of aerobraking, it entered its final science orbit and began its primary science phase.

Springs in Vernal Crater, as seen by HIRISE. Springs are thought to be one of the best places to look for life because molten rock may have kept the area warm enough to support life. Also, fossils can be easily preserved by minerals found in association with hot springs.

MRO contains a host of scientific instruments such as cameras, spectrometers, and radar, which are used to analyze the landforms, stratigraphy, minerals, and ice of Mars. It paves the way for future spacecraft by monitoring daily weather and surface conditions, studying potential landing sites, and hosting a new telecommunications system. MRO's telecommunications system will transfer more data back to Earth than all previous interplanetary missions combined, and MRO will serve as a highly capable relay satellite for future missions.

The mission is managed by the Jet Propulsion Laboratory, at California Institute of Technology, Pasadena, California, for the NASA Science Mission Directorate, Washington, D.C.

Pre-launch

MRO was one of two missions being considered for the 2003 Mars launch window; however, during the proposal process the orbiter lost against what became known as the Mars Exploration Rovers. The orbiter mission was rescheduled for launch in 2005, and NASA announced its final name, *Mars Reconnaissance Orbiter*, on October 26, 2000.

MRO is modeled after NASA's highly successful *Mars Global Surveyor* to conduct surveillance of Mars from orbit. Early specifications of the satellite included a large camera to take high resolution pictures of Mars. In this regard, Jim Garvin, the Mars exploration program scientist for NASA, proclaimed that MRO would be a "microscope in orbit". The satellite was also to include a visible-near-infrared spectrograph.

On October 3, 2001, NASA chose Lockheed Martin as the primary contractor for the spacecraft's fabrication. By the end of 2001 all of the mission's instruments were selected. There were no major setbacks during MRO's construction, and the spacecraft was moved to John F. Kennedy Space Center on May 1, 2005 to prepare it for launch.

Mission objectives

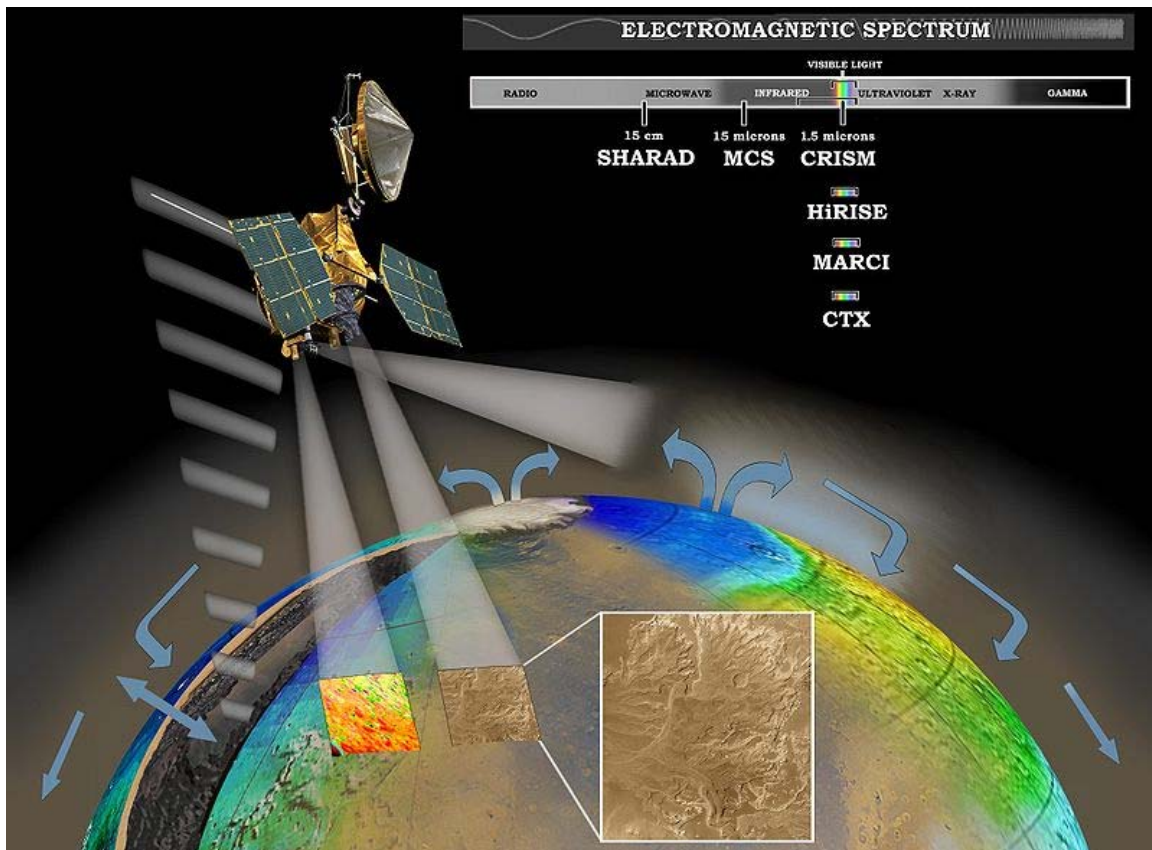


Diagram of instrumentation aboard MRO

MRO science operations were initially scheduled to last two Earth years, from November 2006 to November 2008. One of the mission's main goals is to map the Martian landscape with its high-resolution cameras in order to choose landing sites for future surface missions. The MRO played an important role in choosing the landing site of the Phoenix Lander, which explored the Martian Arctic in Green Valley. The initial site chosen by scientists was imaged with the HiRISE camera and found to be littered with boulders. After analysis with HiRISE and the Mars Odyssey's THEMIS a new site was chosen. *Mars Science Laboratory*, a highly maneuverable rover, will also have its landing site inspected. The MRO will also provide critical navigation data during their landings and act as a telecommunications relay.

MRO is using its on-board scientific equipment to study the Martian climate, weather, atmosphere, and geology, and to search for signs of water in the polar caps and underground. In addition, MRO is looking for the remains of the previously lost Mars Polar Lander and Beagle 2 spacecraft, and serves as the first step in setting up an internet protocol network for the planets in our solar system. After its main science operations are completed, the probe's extended mission is to be the communication and navigation system for landers and rover probes.

Launch and orbital insertion



Launch of Atlas V carrying the Mars Reconnaissance Orbiter, 11:43:00 UTC August 12, 2005

On August 12, 2005, MRO was launched aboard an Atlas V-401 rocket from Space Launch Complex 41 at Cape Canaveral Air Force Station. The Centaur upper stage of the rocket completed its burns over a fifty-six minute period and placed MRO in interplanetary transfer orbit towards Mars.

MRO cruised through interplanetary space for seven and a half months before reaching Mars. While en route most of the scientific instruments and experiments were tested and calibrated. To ensure proper orbital insertion upon reaching Mars, four trajectory correction maneuvers were planned and a fifth emergency maneuver was discussed. However, only three trajectory correction maneuvers were necessary, saving fuel for MRO's extended mission.

MRO began orbital insertion by approaching Mars on March 10, 2006, and passing above its southern hemisphere at an altitude of 370–400 km (190 mi). All six of MRO's main engines burned for 27 minutes to slow the probe from ~2,900 m/s to ~1,900 m/s (6,500 mph to 4,250 mph). The helium pressurization tank was colder than expected, which reduced the pressure in the fuel tank by about 21 kPa (3 psi). The reduced pressure caused the engine thrust to be diminished by 2%, but MRO automatically compensated by extending the burn time by 33 seconds.



Artwork of MRO aerobraking

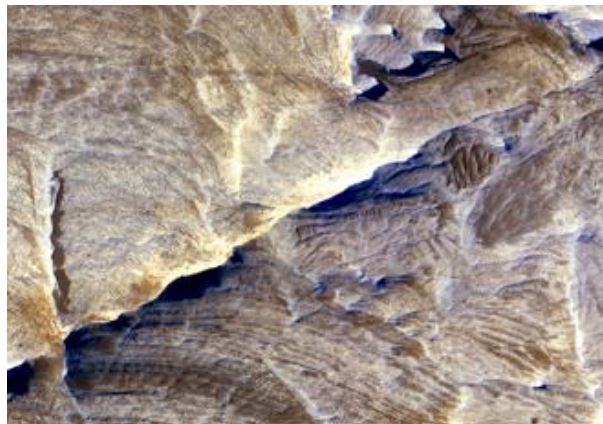
Completion of the orbital insertion placed the orbiter in a highly elliptical polar orbit with a period of approximately 35.5 hours. Shortly after insertion, the periapsis – the point in the orbit closest to Mars – was 3,806 km from the planet's center (426 km from its surface). The apoapsis – the point in the orbit farthest from Mars – was 47,972 km from the planet's center (44,500 km from its surface).

On March 30, 2006, MRO began the process of aerobraking, a three-step procedure that cuts in half the fuel needed to achieve a lower, more circular orbit with a shorter period. First, during its first five orbits of the planet (one Earth week), MRO used its thrusters to drop the periapsis of its orbit into aerobraking altitude. This altitude depends on the thickness of the atmosphere because Martian atmospheric density changes with its seasons. Second, while using its thrusters to make minor corrections to its periapsis altitude, MRO maintained aerobraking altitude for 445 planetary orbits (about 5 Earth months) to reduce the apoapsis of the orbit to 450 km (280 mi). This was done in such a way so as to not heat the spacecraft too much, but also dip enough into the atmosphere to slow the spacecraft down. After the process was complete, MRO used its thrusters to move its periapsis out of the edge of the Martian atmosphere, August 30, 2006.

In September 2006 MRO fired its thrusters twice more to fine-tune its final, nearly circular orbit approximately 250 to 316 km (155 to 196 mi) above the Martian surface. The SHARAD dipole antennas were deployed on September 16. All of the scientific instruments were tested and most were turned off prior to the solar conjunction which occurred from October 7, 2006 to November 6, 2006. After the conjunction ended the "primary science phase" began.

On November 17, 2006 NASA announced the successful test of the MRO as an orbital communications relay. Using the NASA rover "Spirit" as the point of origin for the transmission, the MRO acted as a relay for transmitting data back to Earth.

Events and discoveries



Tectonic fractures within the Candor Chasma region of Valles Marineris, Mars, retain ridge-like shapes as the surrounding bedrock erodes away. This points to past episodes of

fluid alteration along the fractures and reveals clues into past fluid flow and geochemical conditions below the surface.

On September 29, 2006, MRO took its first high resolution image from its science orbit. This image is said to resolve items as small as 90 cm (3 feet) in diameter.

On October 6, 2006, NASA released detailed pictures from the MRO of Victoria crater along with the Opportunity rover on the rim above it.

In November 2006, problems began to surface in the operation of two MRO spacecraft instruments. A stepping mechanism in the Mars Climate Sounder (MCS) skipped on multiple occasions resulting in a field of view that is slightly out of position. By December normal operations of the instrument was suspended, although a mitigation strategy allows the instrument to continue making most of its intended observations. Also, an increase in noise and resulting bad pixels has been observed in several CCDs of the High Resolution Imaging Science Experiment (HiRISE). Operation of this camera with a longer warm-up time has alleviated the issue. However, the cause is still unknown and may return.

HiRISE continues to return images which have enabled discoveries regarding the geology of Mars. Foremost among these is the announcement of banded terrain observations indicating the presence and action of liquid carbon dioxide or water on the surface of Mars in its recent geological past. HiRISE was able to photograph the *Phoenix* lander during its parachuted descent to Vastitas Borealis on May 25, 2008.

The orbiter continued to experience recurring problems in 2009, including four spontaneous resets, culminating in a four-month shut-down of the space craft from August to December. While engineers have not determined the cause of the recurrent resets, they have created new software to help troubleshoot the problem should it recur.

Instruments

Three cameras, two spectrometers and a radar are included on the orbiter along with two "science-facility instruments", which use data from engineering subsystems to collect science data. Three technology experiments will test and demonstrate new equipment for future missions. It is expected MRO will obtain about 5,000 images a year.

HiRISE (camera)



HiRISE camera structure

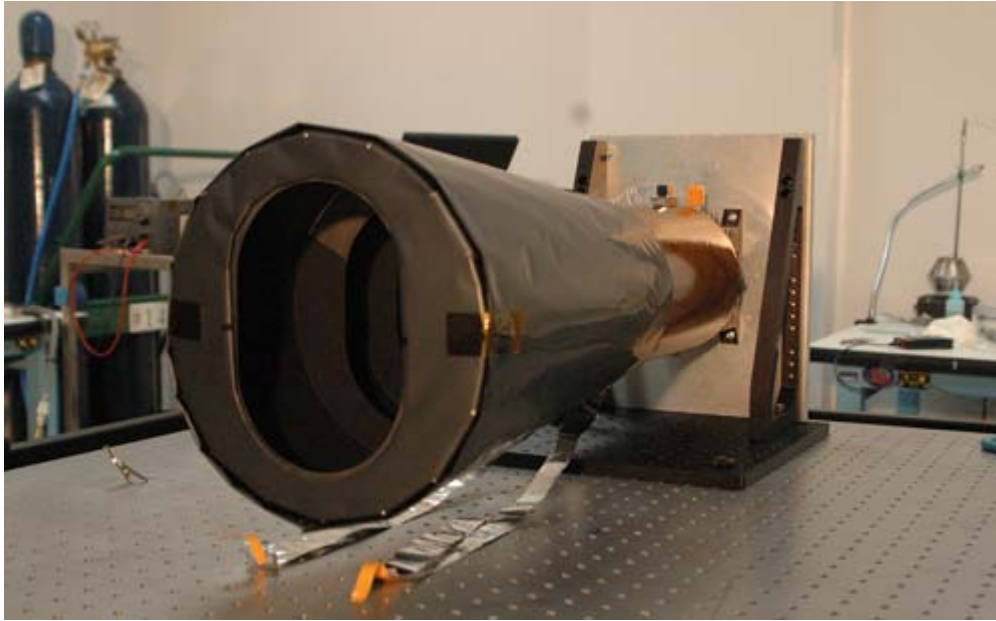
The High Resolution Imaging Science Experiment camera is a 0.5 m reflecting telescope, the largest ever carried on a deep space mission, and has a resolution of 1 microradian (μrad), or 0.3 m from an altitude of 300 km. In comparison, satellite images of Earth are generally available with a resolution of 0.5 m, and satellite images on Google Maps are available to 1 m. HiRISE collects images in three color bands, 400 to 600 nm (blue-green or B-G), 550 to 850 nm (red) and 800 to 1,000 nm (near infrared or NIR).



HiRISE image of the 'face' at Cydonia Mesa

Red color images are 20,264 pixels across (6 km wide), and B-G and NIR are 4,048 pixels across (1.2 km wide). HiRISE's on-board computer reads these lines in time with the orbiter's ground speed, and images are potentially unlimited in length. Practically however, their length is limited by the computer's 28 Gigabit (Gb) memory capacity, and the nominal maximum size is $20,000 \times 40,000$ pixels (800 megapixels) and $4,000 \times 40,000$ pixels (160 megapixels) for B-G and NIR images. Each 16.4 Gb image is compressed to 5 Gb before transmission and release to the general public on the HiRISE website in JPEG 2000 format. To facilitate the mapping of potential landing sites, HiRISE can produce stereo pairs of images from which topography can be calculated to an accuracy of 0.25 m. HiRISE was built by Ball Aerospace & Technologies Corp.

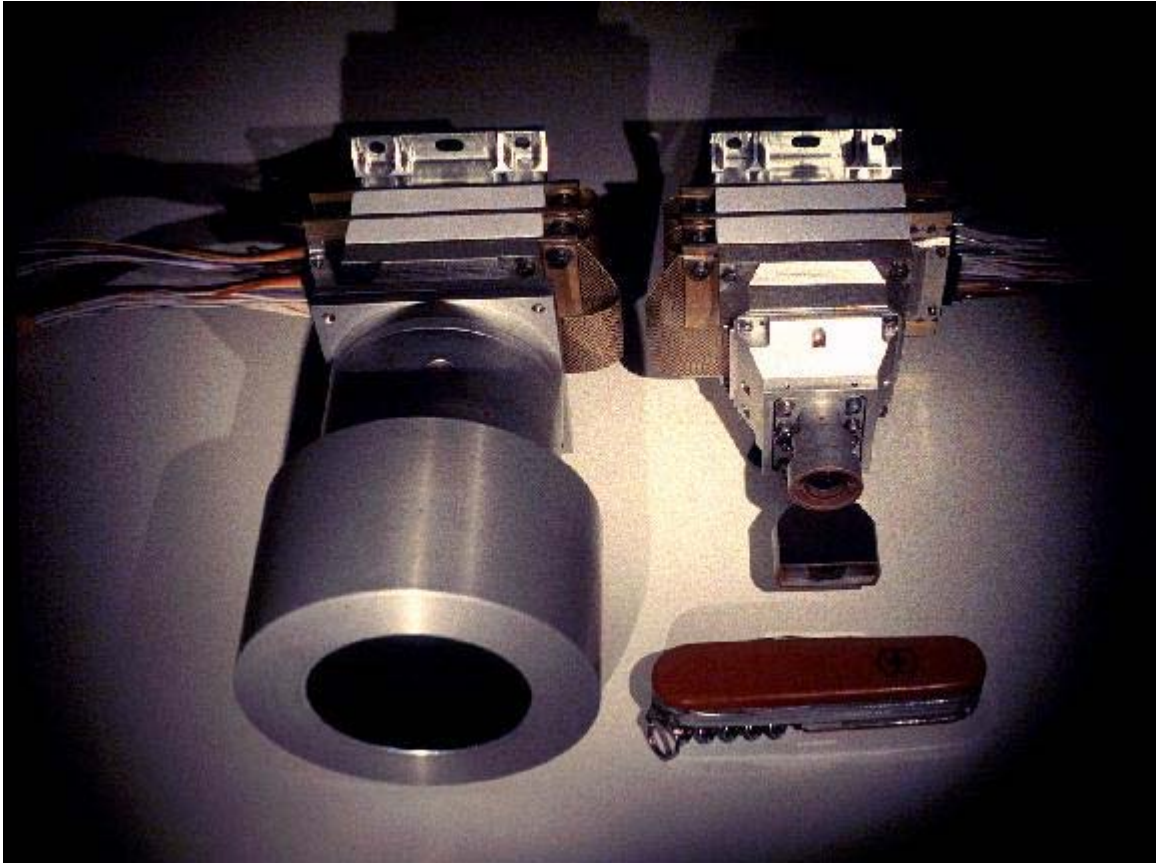
CTX (camera)



Context (CTX) Camera

The Context Camera (CTX) provides grayscale images (500 to 800 nm) with a pixel resolution of 6 m. CTX is designed to provide context maps for the targeted observations of HiRISE and CRISM, and is also used to mosaic large areas of Mars, monitor a number of locations for changes over time, and to acquire stereo (3D) coverage of key regions and potential future landing sites. The optics of CTX consist of a 350 mm focal length Maksutov Cassegrain telescope with a 5,064 pixel wide line array CCD. The instrument takes pictures 30 km (19 mi) wide and has enough internal memory to store an image 160 km long before loading it into the main computer. The camera was built (and is operated by) Malin Space Science Systems.

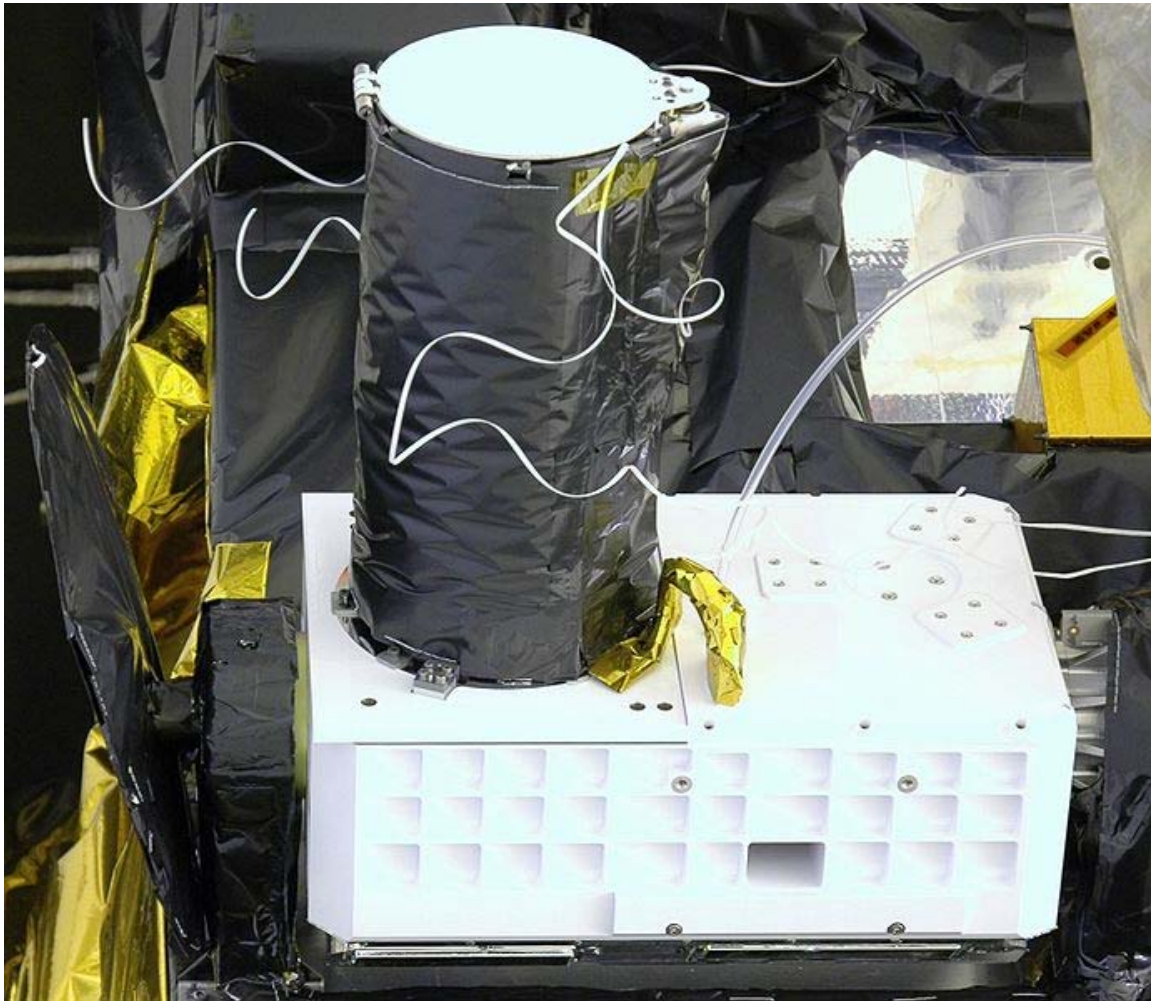
MARCI (camera)



Mars Color Imager

The Mars Color Imager (MARCI) is a wide-angle, low-resolution camera that views the surface of Mars in five visible and two ultraviolet bands. Each day, MARCI collects about 84 images and produces a global map with pixel resolutions of 1 to 10 km. This map provides a daily weather report for Mars, helps to characterize its seasonal and annual variations, and maps the presence of water vapor and ozone in its atmosphere. The camera was built (and is operated by) Malin Space Science Systems.

CRISM (spectrometer)



CRISM Instrument

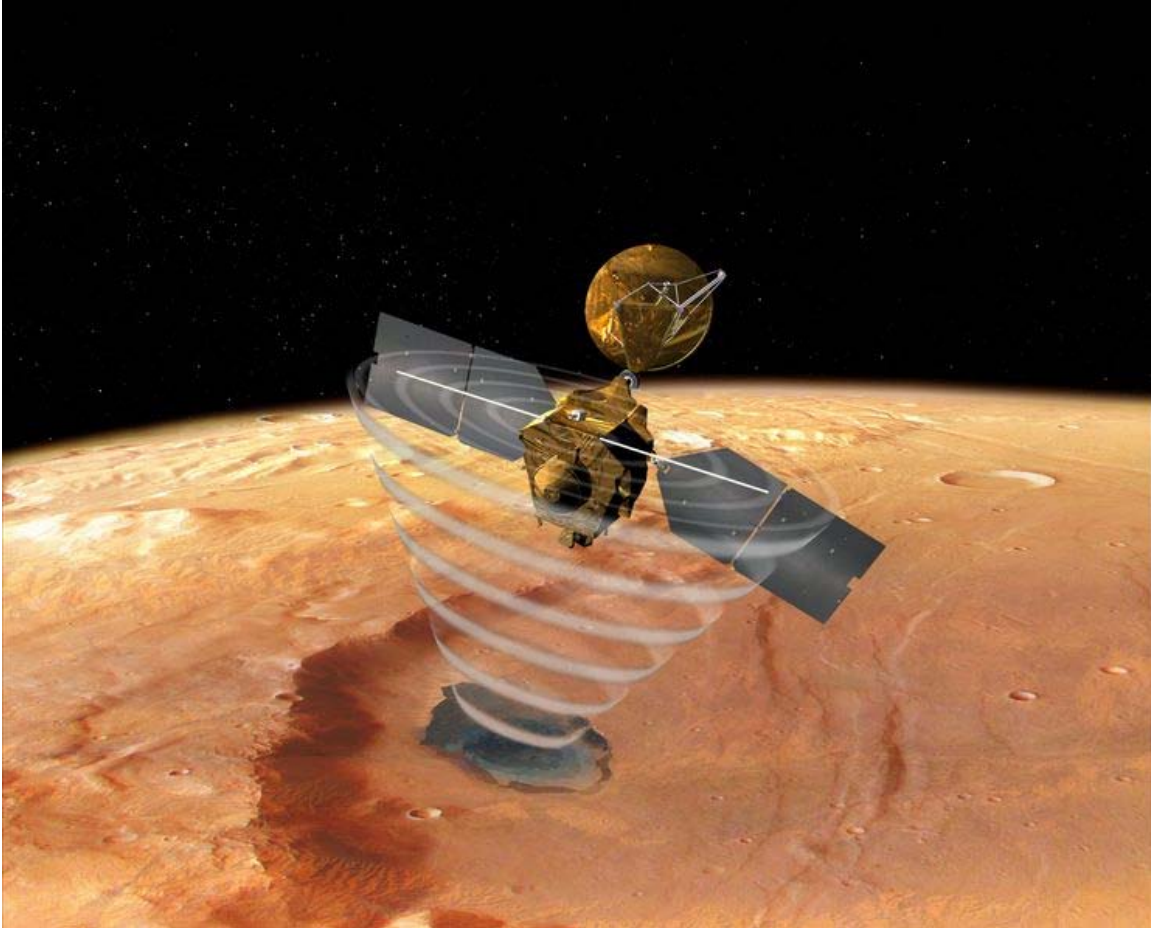
The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument is a visible and near infrared (VNIR) spectrometer that is used to produce detailed maps of the surface mineralogy of Mars. It operates from 370 to 3920 nm, measures the spectrum in 544 channels (each 6.55 nm wide), and has a resolution of 18 m (59 ft) at an altitude of 300 km (190 mi). CRISM is being used to identify minerals and chemicals indicative of the past or present existence of water on the surface of Mars. These materials include iron, oxides, phyllosilicates, and carbonates, which have characteristic patterns in their visible-infrared energy.

MCS (spectrometer)

The Mars Climate Sounder (MCS) is a spectrometer with one visible/near infrared channel (0.3 to 3.0 μm) and eight far infrared (12 to 50 μm) channels. These channels were selected to measure temperature, pressure, water vapor and dust levels. MCS

observes the atmosphere on the horizon of Mars (as viewed from MRO) by breaking it up into vertical slices and taking measurements within each slice in 5 km (3 mi) increments. These measurements are assembled into daily global weather maps to show the basic variables of Martian weather: temperature, pressure, humidity and dust density.

SHARAD (radar)



An artist's concept of MRO using SHARAD to "look" under the surface of Mars

MRO's Shallow Subsurface Radar (SHARAD) experiment is designed to probe the internal structure of the Martian polar ice caps. It also gathers planet-wide information about underground layers of ice, rock and possibly liquid water that might be accessible from the surface. SHARAD uses HF radio waves between 15 and 25 MHz, a range that allows it to resolve layers as thin as 7 m (23 ft) to a maximum depth of 1 km (0.6 mi). It has a horizontal resolution of 0.3 to 3 km (0.2 to 1.9 mi). SHARAD is designed to operate in conjunction with the Mars Express MARSIS, which has lower resolution but penetrates to a much greater depth. Both SHARAD and MARSIS were made by the Italian Space Agency.

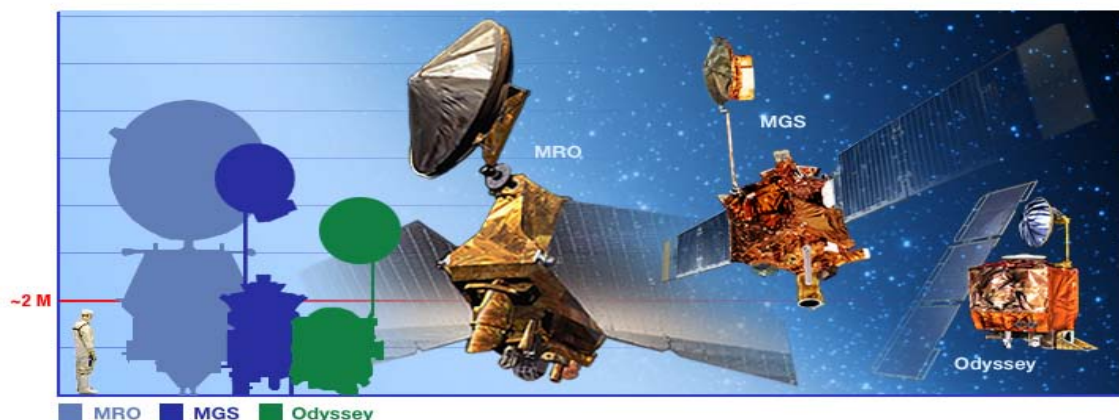
Engineering instruments

In addition to its imaging equipment, MRO carries a variety of engineering instruments. The Gravity Field Investigation Package measures variations in the Martian gravitational field through variations in the spacecraft's velocity. Velocity changes are detected by measuring doppler shifts in MRO's radio signals received on Earth. The package also includes sensitive on-board accelerometers used to deduce the *in situ* atmospheric density of Mars during aerobraking.

The Electra is a UHF software defined radio designed to communicate with other spacecraft as they approach, land, and operate on Mars. In addition to protocol controlled inter-spacecraft data links of 1 kbit/s to 2 Mbit/s, Electra also provides Doppler data collection, open loop recording and a highly accurate timing service based on a 5e-13 USO. Doppler information for approaching vehicles can be used for final descent targeting or descent and landing trajectory recreation. Doppler information on landed vehicles will also enable scientists to accurately determine the surface location of Mars landers and rovers. The two MER spacecraft currently on Mars utilize an earlier generation UHF relay radio providing similar functions through the Mars Odyssey orbiter. The Electra radio has used the MER spacecraft to prove its functionality but it is not scheduled to provide formal relay services until the 2008 arrival of the Phoenix Mars lander. Because the Electra radio is software defined down to the modem level, new modulation, coding or protocol functions can be added or updated while the MRO spacecraft is in orbit around Mars.

The Optical Navigation Camera images the Martian moons, Phobos and Deimos, against background stars to precisely determine MRO's orbit. Although moon imaging is not mission critical, it was included as a technology test for future orbiting and landing of spacecraft. The Optical Navigation Camera was tested successfully in February and March 2006.

Engineering data



Size comparison of MRO with predecessors

Structure

Workers at Lockheed Martin Space Systems in Denver assembled the spacecraft structure and attached the instruments. Instruments were constructed at the Jet Propulsion Laboratory, the University of Arizona Lunar and Planetary Laboratory in Tucson, Arizona, Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, the Italian Space Agency in Rome, and Malin Space Science Systems in San Diego, California. The total cost of the spacecraft was \$720 million USD.

The structure is made of mostly carbon composites and aluminum-honeycombed plates. The titanium fuel tank takes up most of the volume and mass of the spacecraft and provides most of its structural integrity. The spacecraft's total mass is less than 2,180 kg (4,806 lb) with an unfueled dry mass less than 1,031 kg (2,273 lb).

Power systems



The Mars Reconnaissance Orbiter solar panel

MRO gets all of its electrical power from two solar panels, each of which can move independently around two axes (up-down, or left-right rotation). Each solar panel measures 5.35×2.53 m and has 9.5 m^2 (102 ft^2) covered with 3,744 individual photovoltaic cells. Its high-efficiency triple junction solar cells are able to convert more than 26% of the sun's energy directly into electricity and are connected together to produce a total output of 32 volts. At Mars, the two panels produce 1,000 watts of power; in contrast, the panels would generate 3,000 watts in a comparable Earth orbit by being closer to the Sun.

MRO has two nickel-hydrogen rechargeable batteries used to power the spacecraft when it is not facing the sun. Each battery has an energy storage capacity of 50 ampere-hours (180 kC). The full range of the batteries cannot be used due to voltage constraints on the spacecraft, but allows the operators to extend the battery life—a valuable capability, given that battery drain is one of the most common causes of long-term satellite failure. Planners anticipate that only 40% of the batteries' capacities will be required during the lifetime of the spacecraft.

Electronic systems

MRO's main computer is a 133 MHz, 10.4 million transistor, 32-bit, RAD750 processor. This processor is a radiation-hardened version of a PowerPC 750 or G3 processor with a specially-built motherboard. The RAD750 is a successor to the RAD6000. This processor may seem underpowered in comparison to a modern PC processor, but it is extremely reliable, resilient, and can function in solar flare-ravaged deep space. The operating system software is VxWorks and has extensive fault protection protocols and monitoring.

Data is stored in a 160 Gb (20 GB) flash memory module consisting of over 700 memory chips, each with a 256 Mbit capacity. This memory capacity is not actually that large considering the amount of data to be acquired; for example, a single image from the HiRISE camera can be as large as 28 Gb.

Attitude determination

In order to determine the spacecraft's orbit and facilitate maneuvers, sixteen sun sensors – eight primaries and eight backups – are placed around the spacecraft to calibrate solar direction relative to the orbiter's frame. Two star trackers, digital cameras used to map the position of catalogued stars, provide NASA with full, three-axis knowledge of the spacecraft orientation and attitude. A primary and backup Miniature Inertial Measurement Unit (MIMU), provided by Honeywell, measures changes to the spacecraft attitude as well as any non-gravitationally induced changes to its linear velocity. Each MIMU is a combination of three accelerometers and three ring-laser gyroscopes. These systems are all critically important to MRO, as it must be able to point its camera to a very high precision in order to take the high-quality pictures that the mission requires. It has also been specifically designed to minimize any vibrations on the spacecraft, so as to allow its instruments to take images without any distortions caused by vibrations.

Telecommunications system



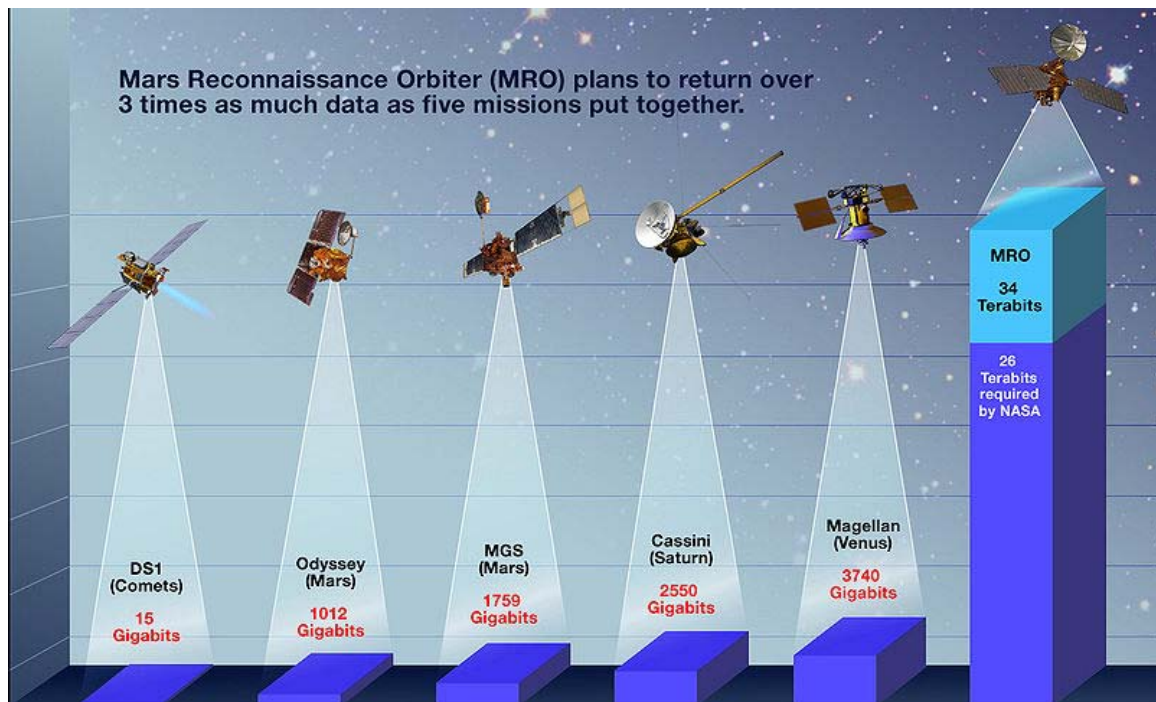
MRO High Gain Antenna installation

The Telecom Subsystem on MRO is the best digital communication system sent into deep space so far and for the first time using capacity achieving turbo-codes. It consists of a very large (3 meter) antenna, which is used to transmit data through the Deep Space Network via X-band frequencies at 8 GHz, and it demonstrates the use of the K_a band at 32 GHz for higher data rates. Maximum transmission speed from Mars is projected to be as high as 6 Mbit/s, a rate ten times higher than previous Mars orbiters. The spacecraft carries two 100-watt X-band amplifiers (one of which is a backup), one 35-watt Ka-band amplifier, and two Small Deep Space Transponders (SDSTs).

Two smaller low-gain antennas are also present for lower-rate communication during emergencies and special events, such as launch and Mars Orbit Insertion. These antennas do not have focusing dishes and can transmit and receive from any direction. They are an important backup system to ensure that MRO can always be reached, even if its main antenna is pointed away from the Earth.

The Ka-band subsystem is used for demonstration purposes. Due to lack of spectrum at 8.41 GHz X-band, future high-rate deep space missions will use 32 GHz Ka-band. NASA Deep Space Network (DSN) has implemented Ka-band receiving capabilities at all three of its complexes (Goldstone, Canberra and Madrid) over its 34-m beam-waveguide (BWG) antenna subnet. MRO Ka-band demonstration will demonstrate viability of Ka-band for deep space operations. During the cruise phase, spacecraft Ka-band telemetry was tracked 36 times by these antennas proving DSN Ka-band reception functionality at all the antennas. During the primary science phase, Ka-band demonstration is assigned two passes a week for Ka-band demonstration purposes. The success of Ka-band during cruise also makes it a viable backup for the X-band subsystem on MRO.

Propulsion and attitude control



Data comparison chart

The spacecraft uses a 1,175 L (310 US gal) fuel tank filled with 1187 kg (2617 lb) of hydrazine monopropellant. Fuel pressure is regulated by adding pressurized helium gas from an external tank. Seventy percent of the fuel was used for orbital insertion.

MRO has twenty rocket engine thrusters on board. Six large thrusters each produce 170 N (38 lbf) of thrust for a total of 1,020 N (230 lbf) meant mainly for orbital insertion. These thrusters were originally designed for the Mars Surveyor 2001 Lander. Six medium thrusters each produce 22 N (5 lbf) of thrust for trajectory correction maneuvers and attitude control during orbit insertion. Finally, eight small thrusters each produce 0.9 N (0.2 lbf) of thrust for attitude control during normal operations.

Four reaction wheels are also used for precise attitude control during activities requiring a highly stable platform, such as high-resolution imaging, in which even small motions can cause blurring of the image. Each wheel is used for one axis of motion. The fourth (skewed) wheel is a backup in case one of the other three wheels fails. Each wheel weighs 10 kg (22 lb) and can be spun as fast as 100 Hz or 6,000 rpm.

Discoveries and photographs

Water ice in ice cap measured

Results, published in 2009, of radar measurements of the North Polar ice cap determined that the volume of water ice in the cap is 821,000 cubic kilometers (197,000 cubic miles). That's equal to 30% of the Earth's Greenland ice sheet.

Ice exposed in new craters



Bright part is water ice that has been exposed by impact. The ice was identified using CRISM on the MRO.

Impressive research, reported in the journal Science in September 2009, has showed that some new craters on Mars show exposed, pure, water ice. After a time, the ice disappears, evaporating into the atmosphere. The ice is only a few feet deep. The ice was confirmed with the Compact Imaging Spectrometer (CRISM) onboard the Mars Reconnaissance Orbiter (MRO). The ice was found in a total of 5 locations. Three of the locations are in the Cebrenia quadrangle. These locations are 55.57° N, 150.62° E; 43.28° N, 176.9° E; and 45° N, 164.5° E. Two others are in the Diacria quadrangle: 46.7° N, 176.8° E and 46.33° N, 176.9° E. This discovery proves that future colonists on Mars will be able to obtain water from a wide variety of locations. The ice can be dug up, melted, then taken apart to provide fresh oxygen and hydrogen for rocket fuel. Hydrogen is the powerful fuel used by the space shuttle main engines.

Lobate debris aprons

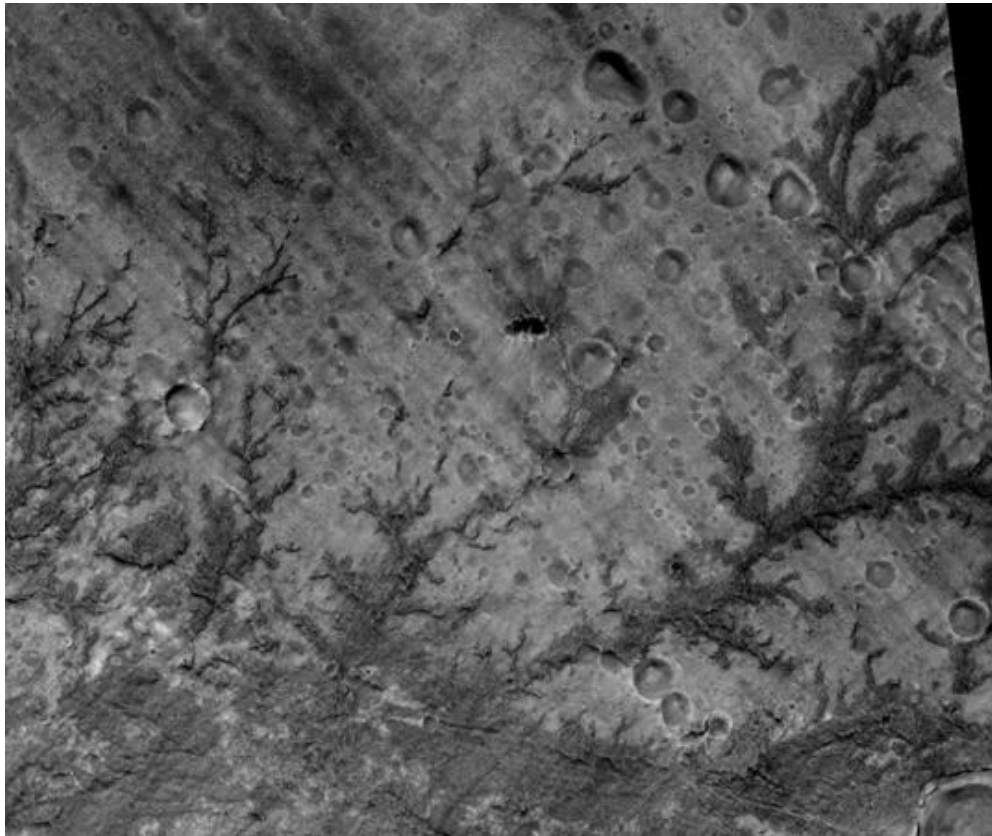


Lobate Debris Apron in Phlegra Montes, Cebrenia quadrangle. The debris apron is probably mostly ice with a thin covering of rock debris, so it could be a source of water for future Martian colonists. Scale bar is 500 meters long.

One of the most important discoveries made by the Mars Reconnaissance Orbiter was that features called Lobate Debris Aprons (LDA's) contain large amounts of water ice. Of

interest from the days of the Viking Orbiters, these LDA's are piles of material surrounding cliffs. They have a convex topography and a gentle slope; this suggests flow away from the steep source cliff. In addition, lobate debris aprons can show surface lineations just as rock glaciers on the Earth. The Shallow Radar on the Mars Reconnaissance Orbiter has provided strong evidence that the LDAs in Hellas Planitia are glaciers that are covered with a thin layer of rocks. Radar from the Mars Reconnaissance Orbiter gave a strong reflection from the top and base of LDAs, meaning that pure water ice made up the bulk of the formation (between the two reflections). Based on the experiments of the Phoenix lander and the studies of the Mars Odyssey from orbit, frozen water is known to exist a just under the surface of Mars in the far north and south (high latitudes). The discovery of water ice in LDA's demonstrates that water is found at even lower latitudes. Future colonists on Mars will be able to tap into these ice deposits, instead of having to travel to much higher latitudes. Another major advantage of LDA's over other sources of Martian water is that they can easily be detected and mapped from orbit. Lobate Debris Aprons are shown below from the Phlegra Montes which are at a latitude of 38.2 degrees north. The Phoenix lander set down at about 68 degrees north latitude, so the discovery of water ice in LDA's greatly expands the range of easily available water on Mars. It is far easier to land a spaceship near the equator of Mars, so the closer water is available to the equator the better it will be for future colonists.

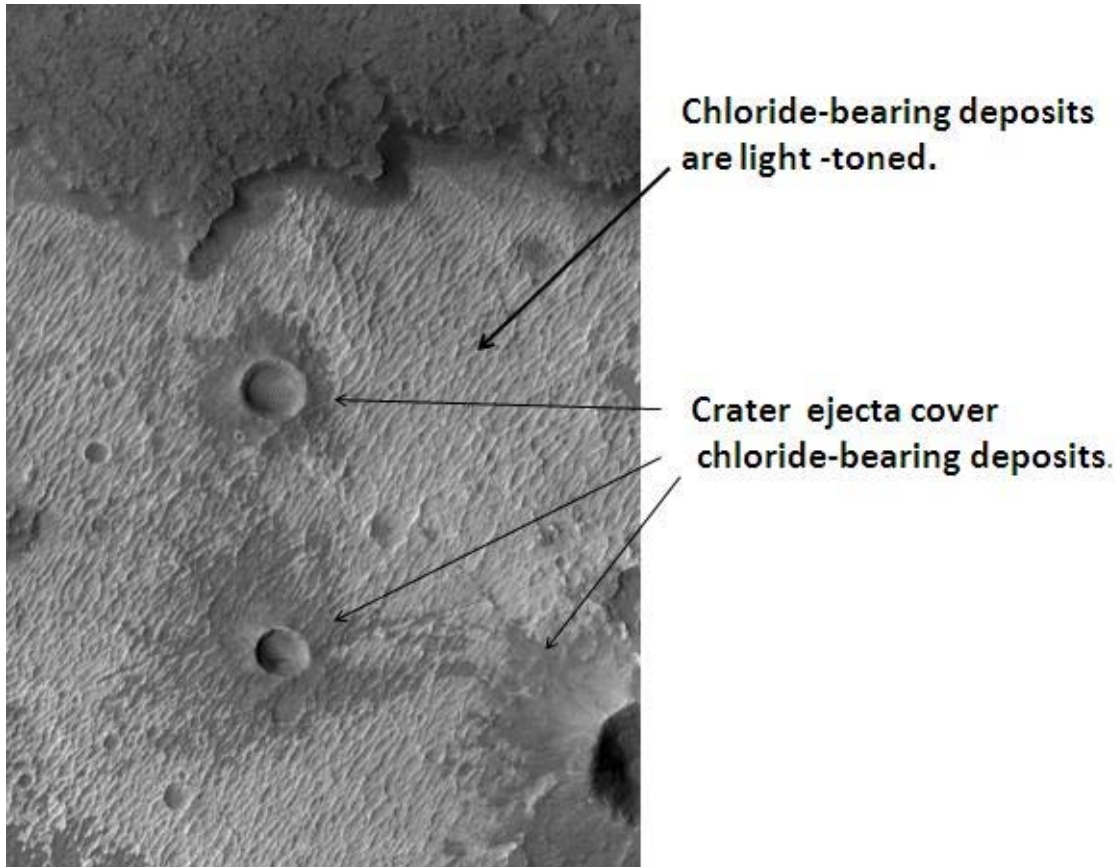
Inverted relief



Inverted Stream Channels in Antoniadi Crater, as seen by HiRISE

Some places on Mars show inverted relief. In these locations, a stream bed may be a raised feature, instead of a valley. The inverted former stream channels may be caused by the deposition of large rocks or due to cementation. In either case erosion would erode the surrounding land and leave the old channel as a raised ridge because the ridge will be more resistant to erosion. An image below, taken with HiRISE of Antoniadi Crater shows sinuous ridges that are old channels that have become inverted.

Chloride deposits



Evidence of water from chloride deposits in Phaethontis. Picture from HiRISE.

Using data from Mars Global surveyor, Mars Odyssey and the Mars Reconnaissance Orbiter, scientists have found widespread deposits of chloride minerals. A picture below shows some deposits within the Phaethontis quadrangle. Evidence suggests that the deposits were formed from the evaporation of mineral enriched waters. The research suggests that lakes may have been scattered over large areas of the Martian surface. Usually chlorides are the last minerals to come out of solution. Carbonates, sulfates, and silica should precipitate out ahead of them. Sulfates and silica have been found by the Mars Rovers on the surface. Places with chloride minerals may have once held various life forms. Furthermore, such areas should preserve traces of ancient life.

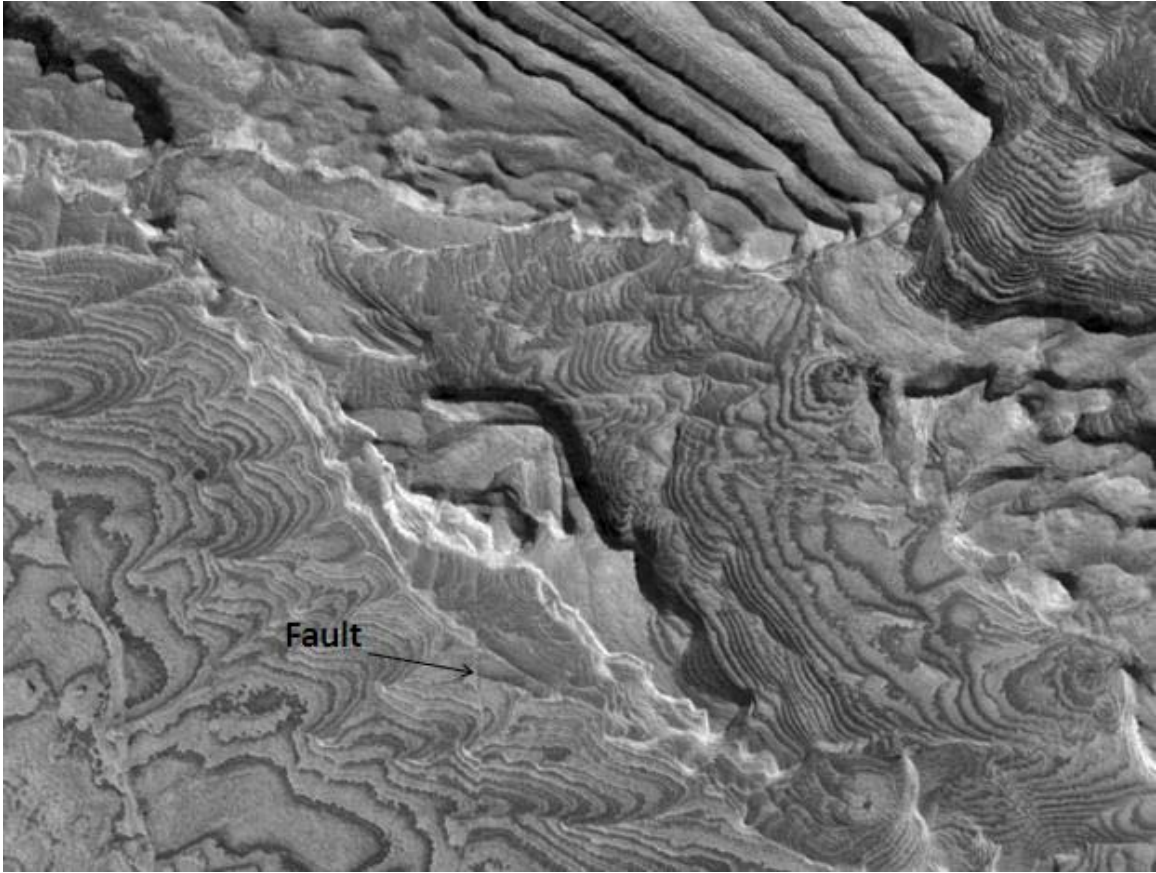
Other aqueous minerals

In a 2009 paper a large group of scientists reported on 9 to 10 different classes of minerals formed in the presence of water. Different types of clays (also called phyllosilicates) were found in many locations. The phyllosilicates identified included aluminum smectite, iron/magnesium smectite, kaolinite, prehnite, and chlorite. Rocks containing carbonate were found around the Isidis basin. Carbonates belong to one class in which life could have developed. Areas around Valles Marineris were found to contain hydrated silica and hydrated sulfates. The researchers identified hydrated sulfates and ferric minerals in Terra Meridiani and in Valles Marineris. Other minerals found on Mars were jarosite, alunite, hematite, opal, and gypsum. Two to five of the mineral classes were formed with the right pH and sufficient water to permit life to grow.

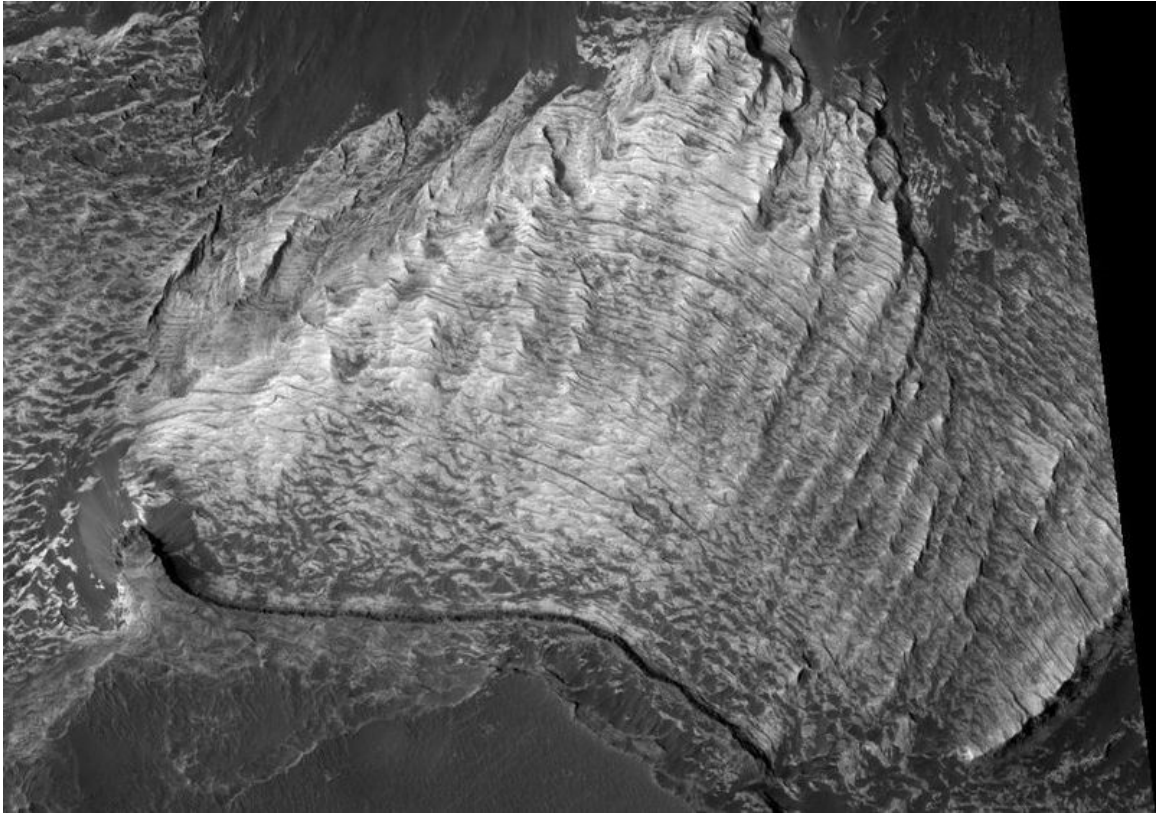
Layers

Columbus Crater contains layers, also called strata. Many places on Mars show rocks arranged in layers. Sometimes the layers are of different colors. Light-toned rocks on Mars have been associated with hydrated minerals like sulfates. The Mars Rover Opportunity examined such layers close-up with several instruments. Some layers are probably made up of fine particles because they seem to break up into fine dust. Other layers break up into large boulders so they are probably much harder. Basalt, a volcanic rock, is thought to be in the layers that form boulders. Basalt has been identified on Mars in many places. Instruments on orbiting spacecraft have detected clay (also called phyllosilicates) in some layers. Scientists are excited about finding hydrated minerals such as sulfates and clays on Mars because they are usually formed in the presence of water. Places that contain clays and/or other hydrated minerals would be good places to look for evidence of life.

Rock can form layers in a variety of ways. Volcanoes, wind, or water can produce layers.



Becquerel Crater layers, as seen by HiRISE.



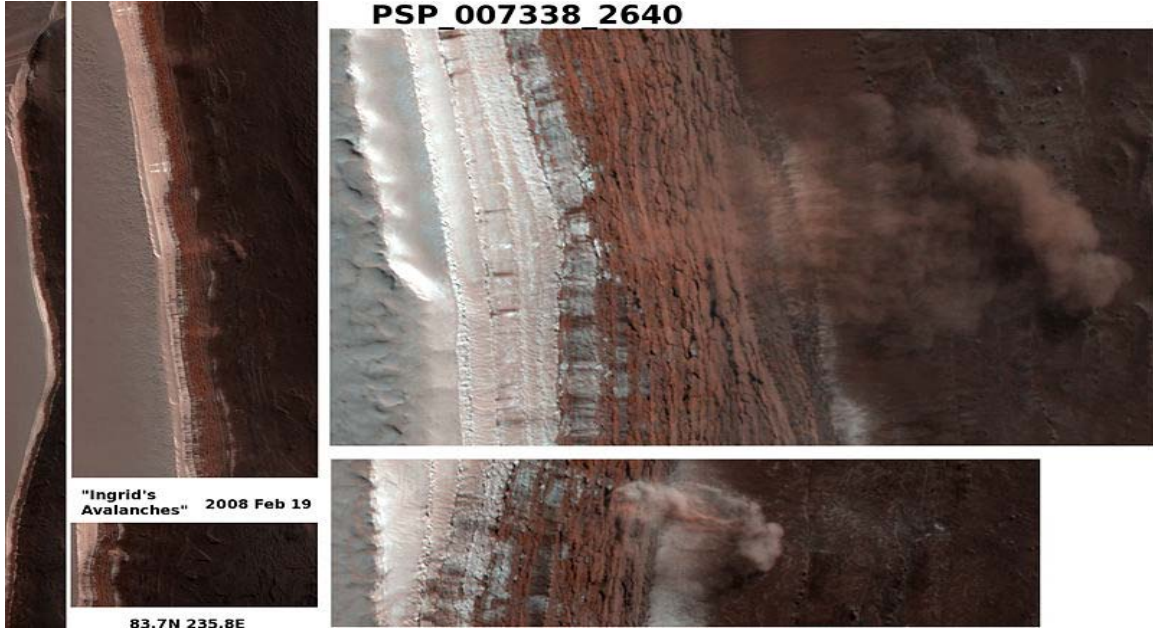
Light colored layers in Eos Chaos, as seen by HiRISE



Columbus Crater Layers, as seen by HiRISE. This false-color image is about 800 feet across. Some of the layers contain hydrated minerals.

Avalanche

On February 19, 2008, Mars Reconnaissance Orbiter photographed an avalanche as it was occurring.



Martian avalanche and debris falls (HiRISE 2008)

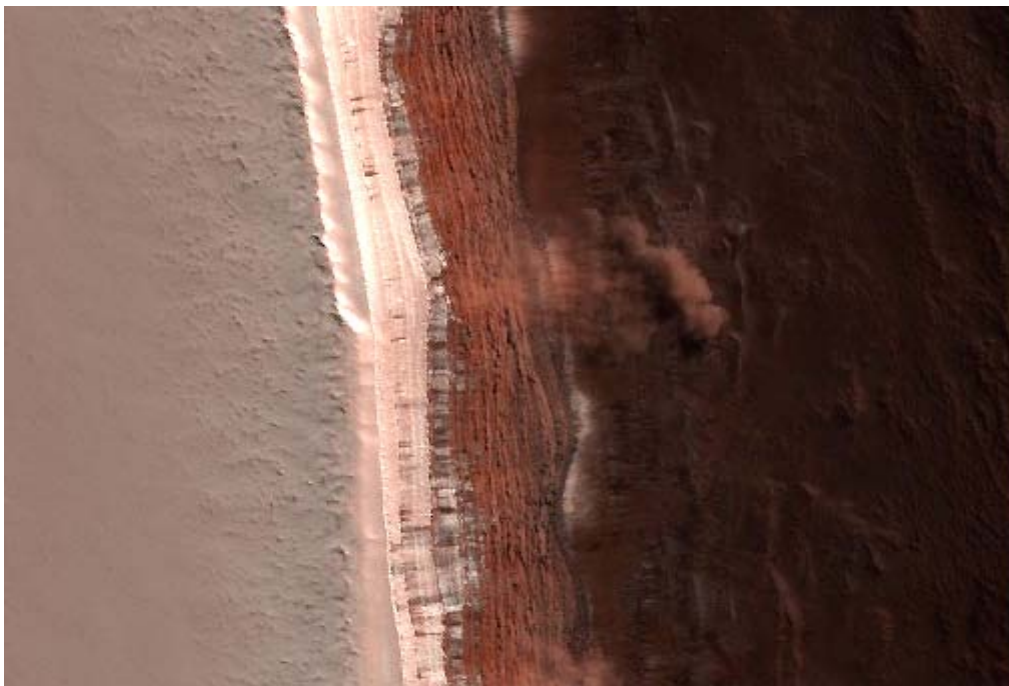


Image of the February 19, 2008 Mars avalanche captured by the Mars Reconnaissance Orbiter.



Closer shot of the avalanche



Dust clouds rise above the 2,300-foot (700 m) deep cliff

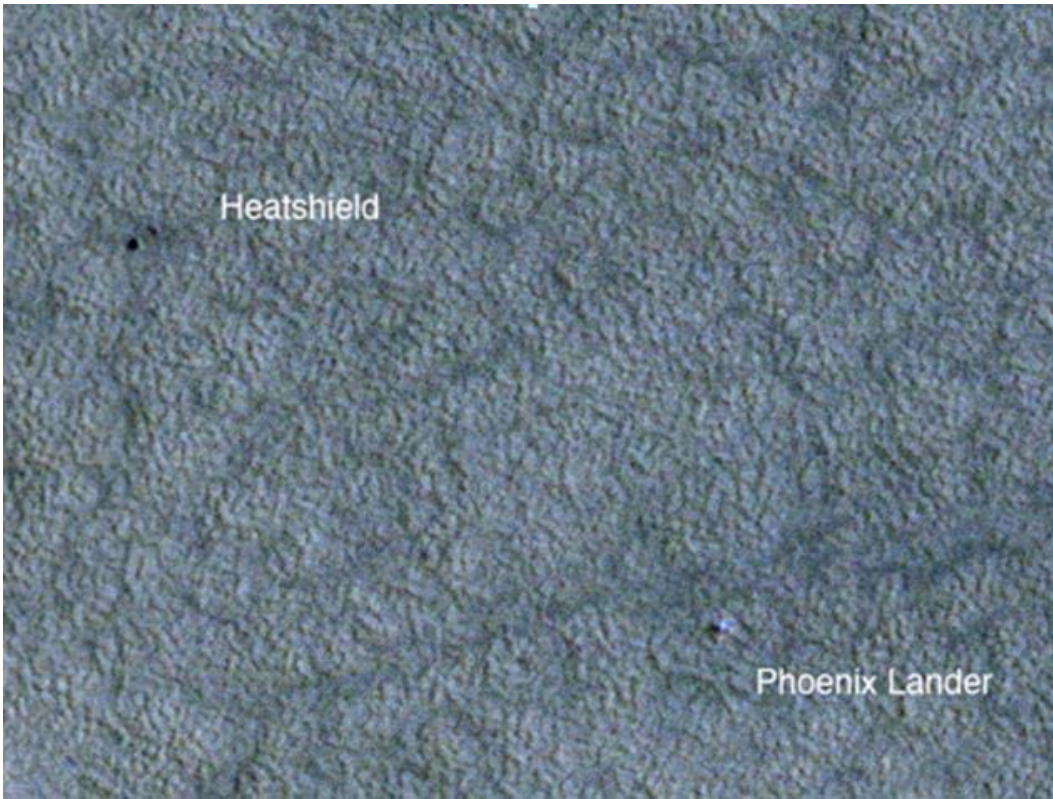


A photo with scale demonstrates the size of the avalanche

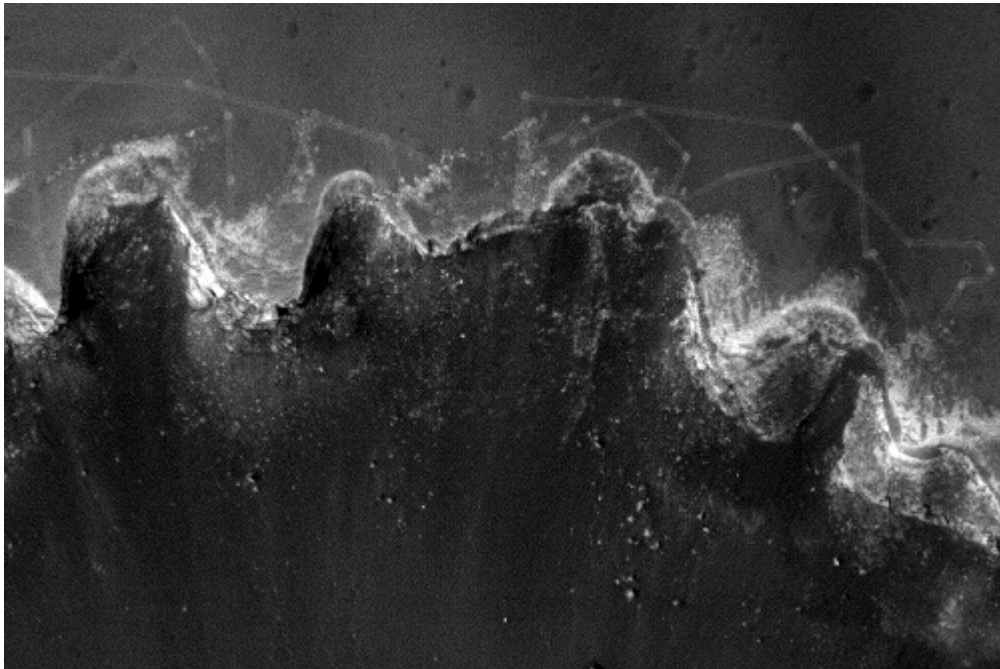
Other spacecraft



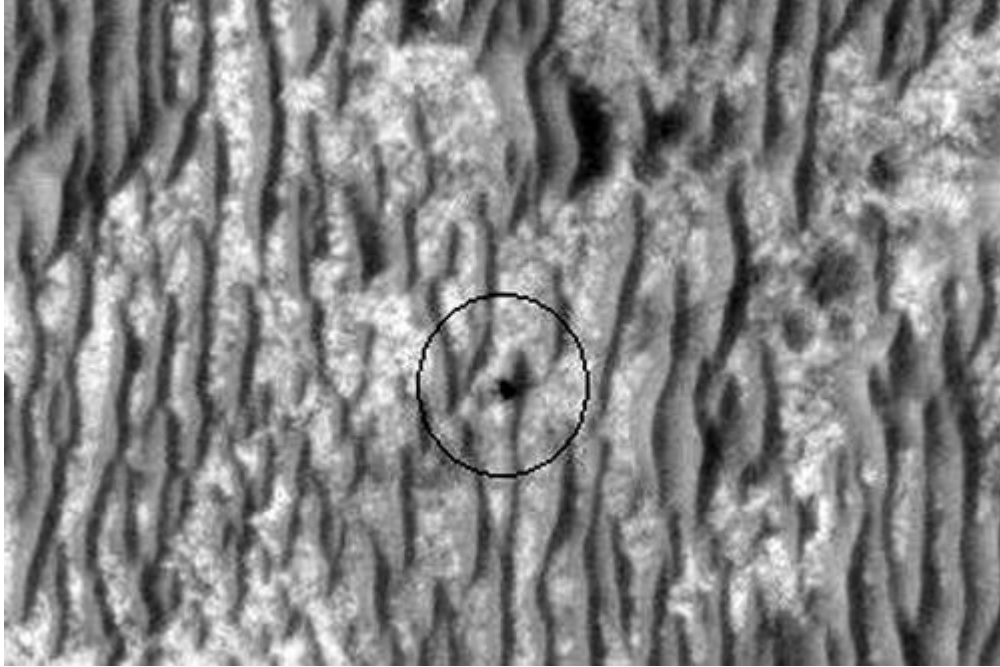
Image of Phoenix landing on Mars, as seen by HiRISE. Although in the image it appears to be descending into the crater, Phoenix actually landed 20 km away from it.



The Phoenix lander and its heatshield as seen by HiRISE



Tracks of the rover Opportunity, as seen by HiRISE. The white dots are places where the rover stopped to perform scientific observations or turned.



Opportunity as seen by HiRISE on January 29, 2009. Opportunity is on its way to Endeavour Crater, 17 km away at this point.