Handbook of Space and Solar System Exploration in 1990s

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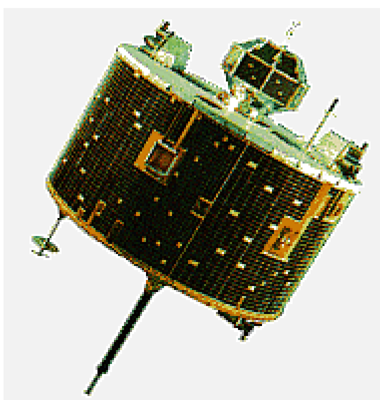
Chapter- 1

Space and Solar System Exploration in 1990

Hiten

Hiten-Hagoromo (Muses-A)



Hiten spacecraft

Operator	ISAS
Mission type	Orbiter
Satellite of	**Moon**
Orbital insertion date	19 March 1990
Orbits	10
Launch date	11:46, 24 January 1990 UTC
Launch vehicle	Mu-3S-II (no. 5)
Mission duration	3 years, 2 months
COSPAR ID	1990-007A
Homepage	Hiten

Mass 197.4 kg

The **Hiten** Spacecraft, given the English name **Celestial Maiden** and known before launch as **MUSES-A** (Mu Space Engineering Spacecraft A), part of the MUSES Program, was built by the Institute of Space and Astronautical Science of Japan and launched on January 24, 1990. It was Japan's first lunar probe, the first robotic lunar probe since the Soviet Union's Luna 24 in 1976, and the first lunar probe launched by a country other than Soviet Union or the United States. Hiten was designed to be an Earth to Moon orbiting spacecraft and testing into deep space maneuver using swing-by to the Moon and aerobraking of the Earth. The spacecraft entered a Double Moon swing-by orbit and released a small orbiter, **Hagoromo** (named after the feather mantle of *Hiten*), into lunar orbit at the first swing-by to the Moon. The transmitter on Hagoromo failed (the only mission payload of Hagoromo is a beacon transmitter, so it is small error to ISAS). ISAS considered Hagoromo to have succeeded by optical observation from earth. After tenth Swing-by to the Moon and second aero-braking mission, (the final mission that was planned before launching) Hiten had some fuel to change her orbit. An additional mission was designed by Edward Belbruno and ISAS. This low energy lunar transfer used Weak Stability Boundary Theory. This, however, would take several months instead of several days. Lastly, Hiten went into circumlunar Moon orbit.

Hiten successfully demonstrated aerobraking technique on March 19 and 30, 1991. This was the first aerobraking maneuver by a deep space probe.

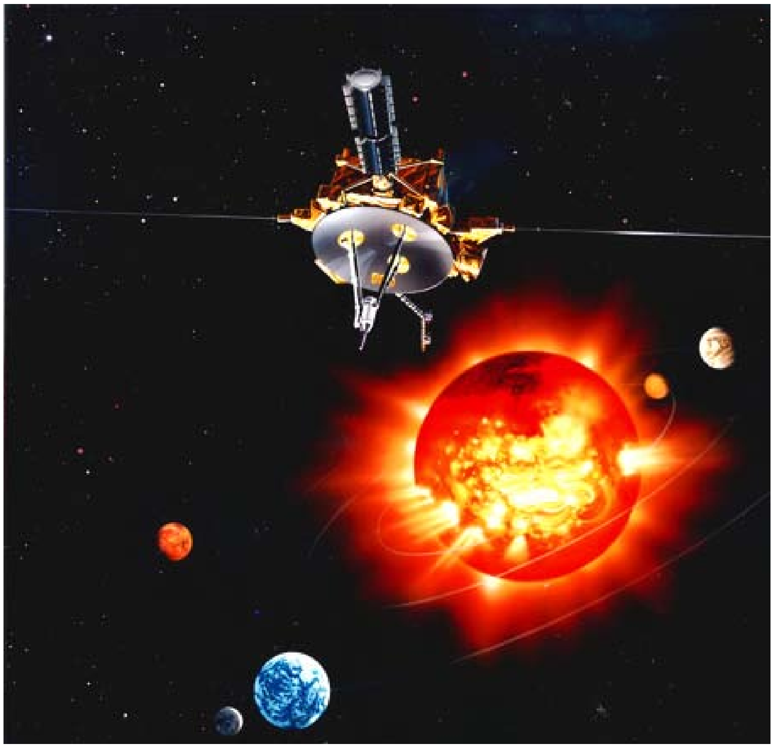
The primary mission was concluded on March 30, 1991 and the follow-on mission was started. On April 24, 1991 Hiten left Earth orbit and went to the Moon using Belbruno's route. On October 2, 1991 Hiten reached the Moon at the prescribed distance. After which, it was put into a looping orbit which passed through the L_4 and L_5 Lagrange points to look for trapped dust particles. No obvious increase was found by the Munich Dust Counter (MDC). After two months in lunar orbit, the spacecraft's orbit was decaying, so the last of Hiten's fuel was used to crash it into the lunar surface on April 10, 1993.

This mission marked the first use of a low-energy (weak stability boundary) transfer to modify an orbit and the first use of a transfer to the Moon requiring no delta V for capture.

The only scientific instrument on Hiten was the Munich Dust Counter (MDC). The MDC provided data on the dust environment between the earth and the moon until April 10, 1993 when Hiten was intentionally crashed into the lunar surface at 34°18′S 55°36′E / 34.3°S 55.6°E between the craters Stevinus and Furnerius.

Ulysses

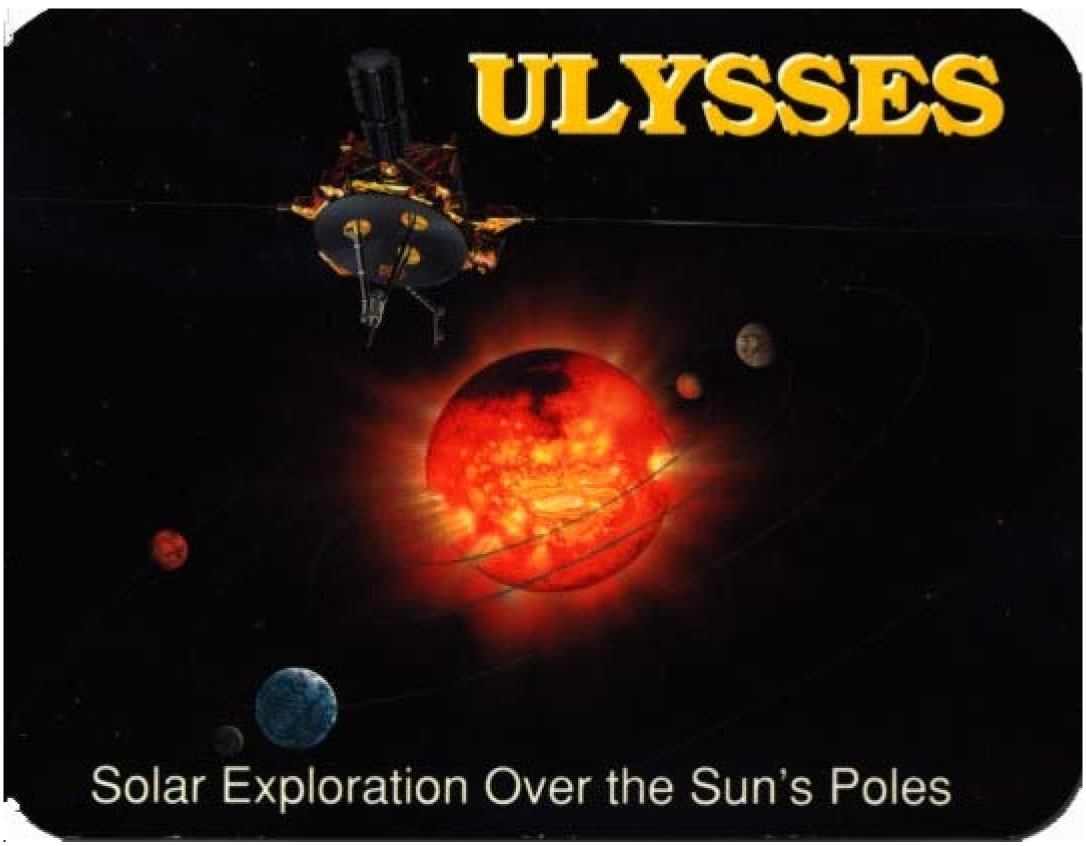
Ulysses



Artist rendering of Ulysses spacecraft.

Operator	NASA / ESA
Mission type	Orbiter
Flyby of	Jupiter
Satellite of	Sun
Launch date	1990-10-06 11:47:16 UTC (20 years, 3 months, and 10 days ago)
Launch vehicle	Space Shuttle Discovery (STS-41) / Inertial Upper Stage / PAM-S
Launch site	KSC Launch Complex 39B Kennedy Space Center
Mission duration	June 26, 1994 - June 30, 2009 (communications terminated)

	Jupiter flyby *(completed 1992-02-08)*
COSPAR ID	1990-090B
Homepage	NASA Page ESA Page
Mass	370 kg (816 lb)
Power	285 W (RTG)

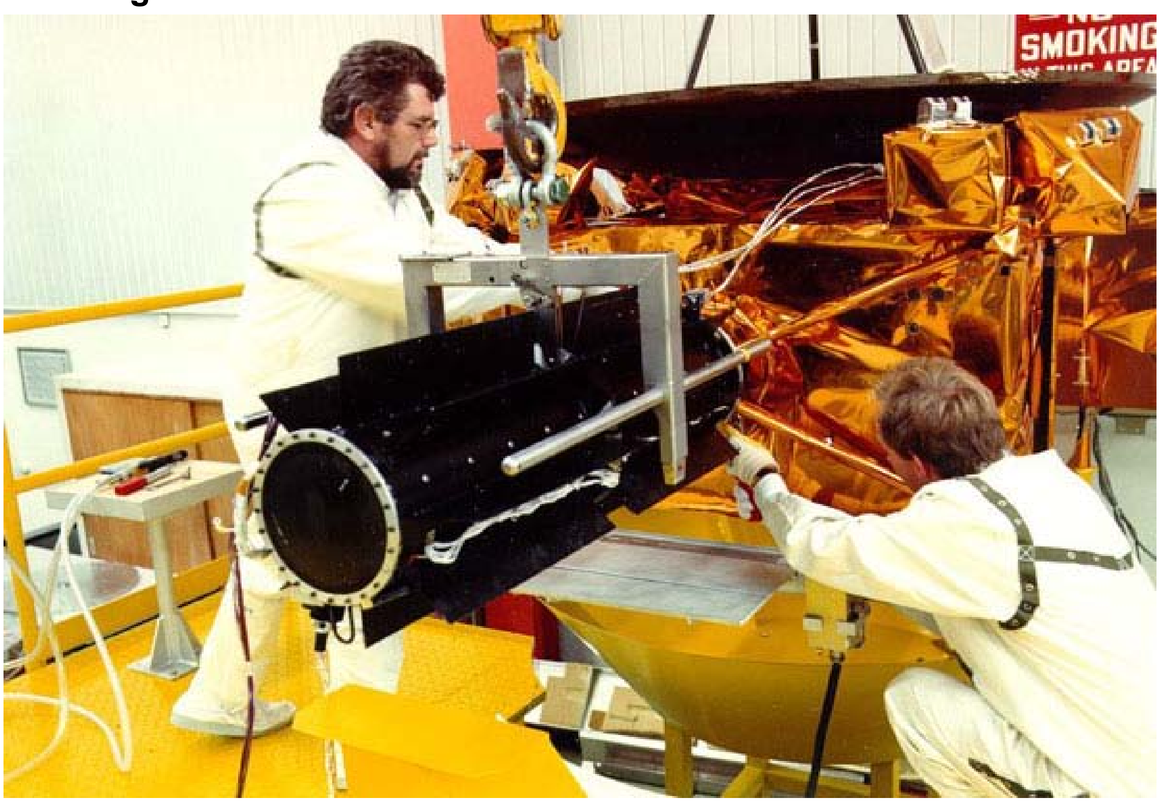


Ulysses was a robotic space probe designed to study the Sun as a joint venture of NASA and the European Space Agency (ESA). The spacecraft was originally named Odysseus, because of its lengthy and indirect trajectory to near Solar distance. It was renamed Ulysses, the Latin translation of "Odysseus" at ESA's request in honour not only of Homer's mythological hero but also with reference to Dante's description in Dante's Inferno, Originally scheduled for launch in 1986 aboard the Space Shuttle Challenger, due to the loss of Challenger, the launch of Ulysses was delayed until October 6, 1990 aboard the Space Shuttle *Discovery* (mission STS-41). The spacecraft's mission was to study the Sun at all latitudes. To do this required a major orbital plane shift. Due to velocity change limitations of the Shuttle and the Inertial Upper Stage (IUS), this was accomplished by using an encounter with Jupiter to effect the plane change instead of an engine burn. The need for a Jupiter encounter meant that Ulysses could not be powered by Solar cells and was powered by a radioisotope thermoelectric generator (RTG) instead.

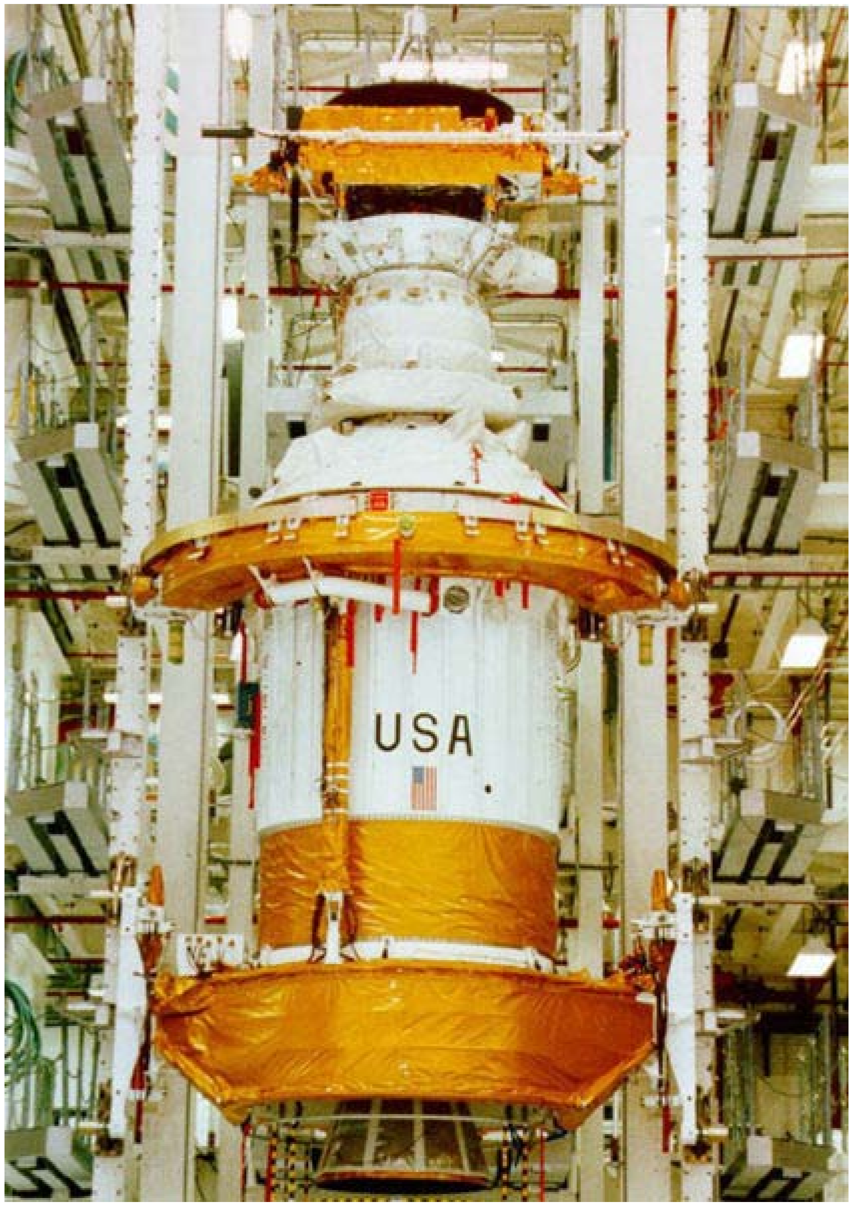
By February 2008, the power output from the RTG, which is generated by heat from the radioactive decay of plutonium-238, had decreased enough to leave insufficient power for internal heaters to keep the spacecraft's attitude control hydrazine fuel from freezing. The end of mission was at one point scheduled for July 1, 2008, but mission scientists came up with a method to keep the fuel liquid by conducting a short thruster burn every two hours, allowing the mission to continue. The cessation of mission operations and deactivation or hibernation of the spacecraft was determined by the inability to prevent attitude control fuel from freezing. The last day for mission operations on Ulysses was 30 June 2009. This was a full year after the most recent previously announced mission end date. The scheduled end of mission in 2009 was the fourth time that the end of the spacecraft's mission had been scheduled. The last scheduled ground station pass of the mission was over the Madrid Deep Space Network 70m ground station (DSS-63) from around 15:35 to 20:20 UTC. There were no decommissioning engineering tests on the spacecraft.

Mission

Planning



Ulysses RTG



Ulysses sits atop the PAM-S and IUS combination

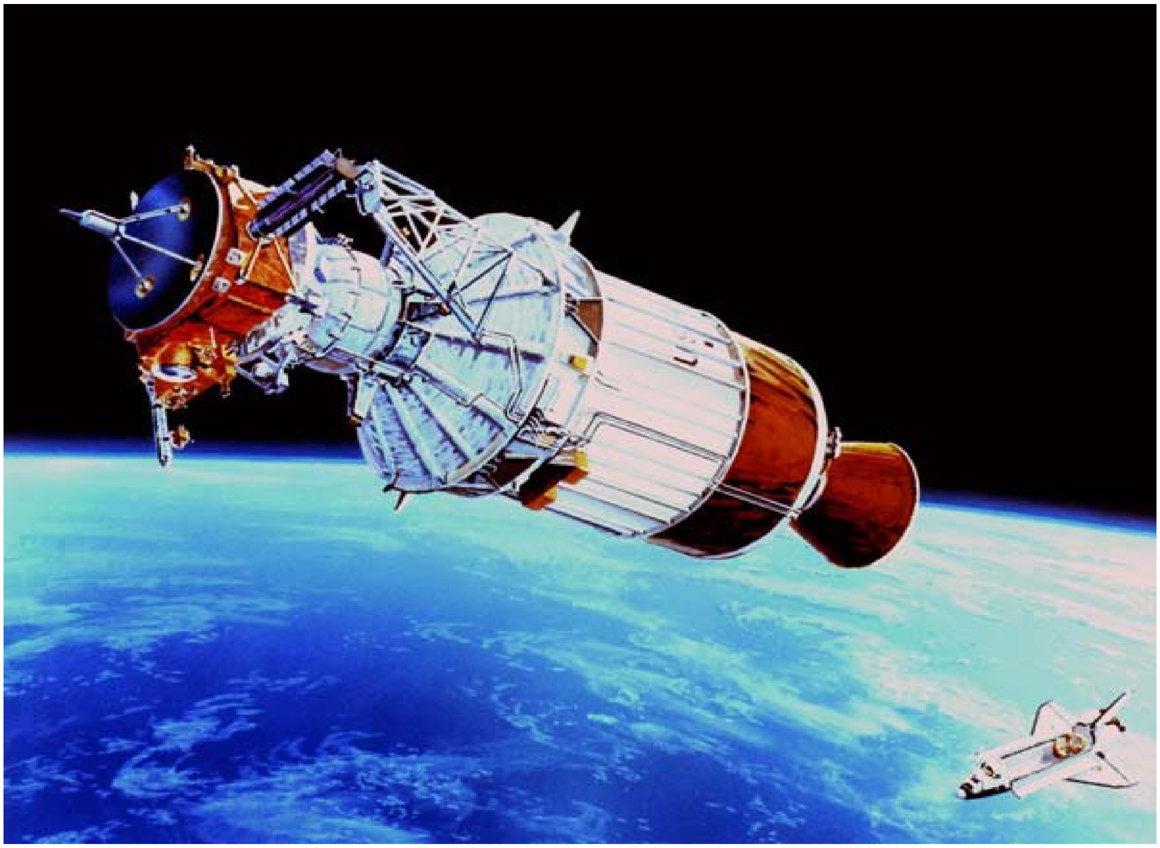
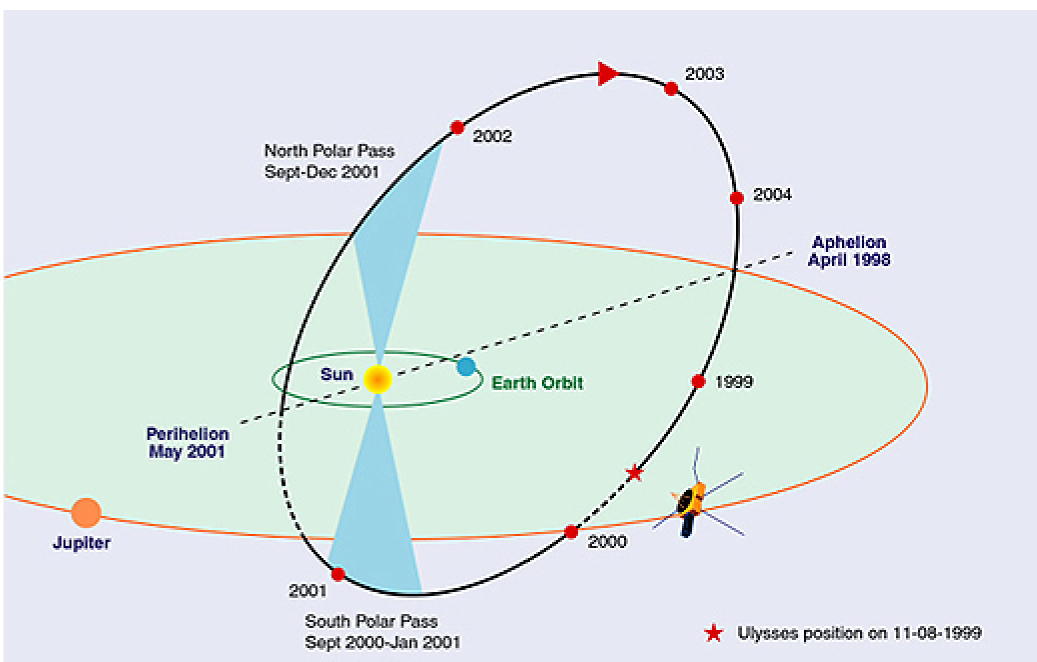
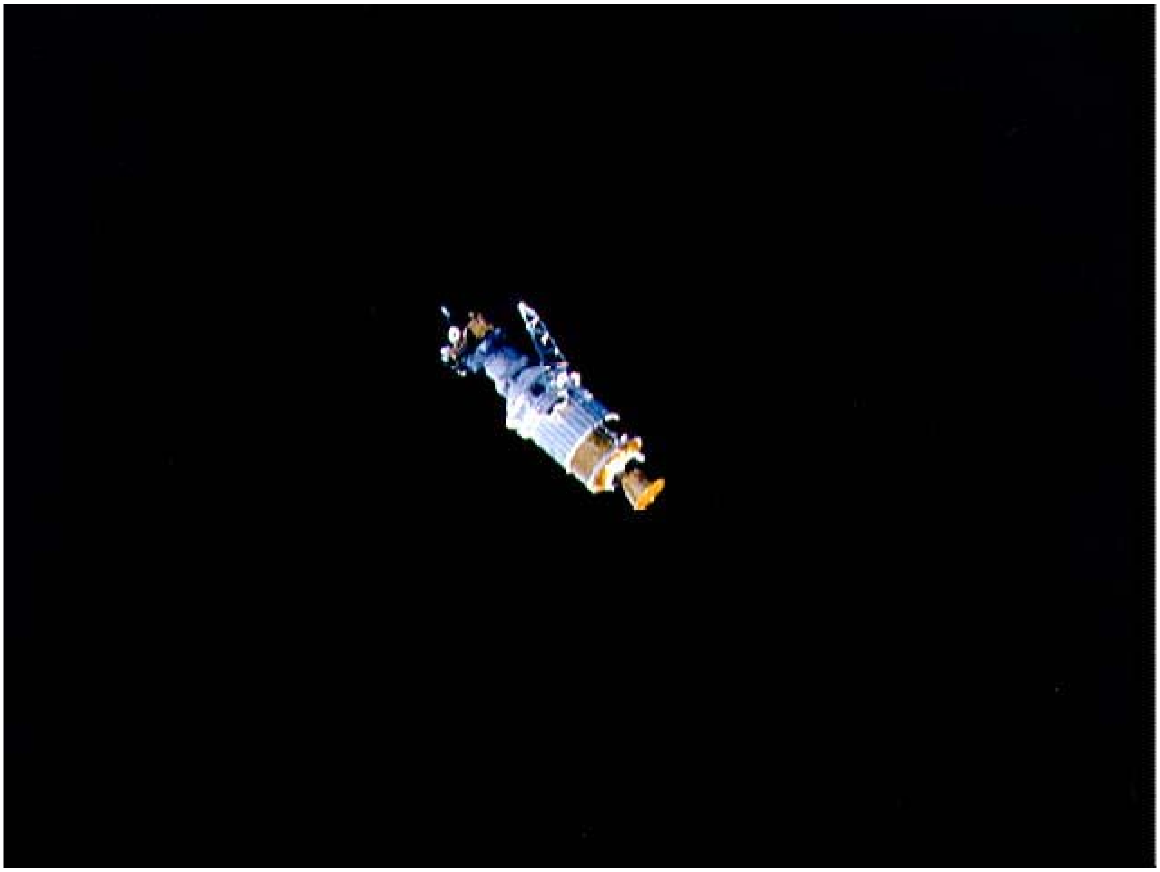


Illustration of Ulysses after deployment



Ulysses' second orbit



Ulysses after deployment from STS-41

Until Ulysses, the Sun was only observed from low solar latitudes. The Earth's orbit defines the ecliptic plane, which differs from the Sun's equatorial plane by only 7.25 degrees. Even spacecraft directly orbiting the Sun do so in planes close to the ecliptic because a direct launch into a high inclination solar orbit would require a prohibitively large launch vehicle.

Several spacecraft (Mariner 10, Pioneer 11, and Voyagers 1 and 2) had performed gravity assist manoeuvres in the 1970s. Those manoeuvres were to reach other planets also orbiting close to the ecliptic, so they were mostly in-plane changes. However, gravity assists are not limited to in-plane maneuvers; a suitable flyby of Jupiter could produce a significant plane change. An Out-Of-The-Ecliptic mission (OOE) was thereby proposed.

Originally, two spacecraft were to be built by NASA and ESA, as the **International Solar Polar Mission.** One would be sent over Jupiter, then under the Sun. The other would fly under Jupiter, then over the Sun. This would provide simultaneous coverage. Due to cutbacks, the US spacecraft was canceled in 1981. One spacecraft was designed, and the project recast as *Ulysses,* due to the indirect and untried flight path. NASA would provide the Radioisotope Thermoelectric Generator (RTG) and launch services, ESA would build the spacecraft assigned to Astrium GmbH, Friedrichshafen, Germany (formerly Dornier Systems). The instruments would be split into teams from universities and research institutes in Europe and the United States. This process provided the 10 instruments on board.

The changes delayed launch from February 1983 to May 1986 where it was to be deployed by the *Space Shuttle Challenger*, however, the Challenger disaster pushed the date to October 1990.

Launch

Ulysses was deployed into low-Earth orbit from the Space Shuttle Discovery. From there, it was propelled on a trajectory to Jupiter by a combination of solid rocket motors. This upper stage consisted of a two-stage Boeing IUS (Inertial Upper Stage), plus a McDonnell Douglas PAM-S (Payload Assist Module-Special). The IUS was inertially stabilised and actively guided during its burn. The PAM-S was unguided and it and the Ulysses spacecraft was spun up to 80 rpm for stability at the start of its burn. On burnout of the PAM-S, the motor and spacecraft stack was yo-yo de-spun (weights deployed at the end of cables) to below 8 rpm prior to separation of the spacecraft. On leaving Earth, the spacecraft became the fastest ever artificially-accelerated object, and held that title until the New Horizons probe was launched.

On its way to Jupiter the spacecraft was in an elliptical Hohmann transfer orbit with perihelion near 1 AU and aphelion near 5 AU, Jupiter's distance from the Sun. At this time Ulysses had a low orbital inclination to the ecliptic.

Jupiter swing-by

It arrived at Jupiter February 8, 1992 for a swing-by maneuver that increased its inclination to the ecliptic by 80.2 degrees. The giant planet's gravity bent the spacecraft's flight path downward and away from the ecliptic plane. This put it into a final orbit around the Sun that would take it past the Sun's north and south poles. The size and shape of the orbit were adjusted to a much smaller degree so that aphelion remained at approximately 5 AU, Jupiter's distance from the Sun, and perihelion was somewhat greater than 1 AU, the Earth's distance from the Sun.

Solar northern polar regions

Between 1994 and 1995 it explored both the southern and northern solar polar regions, respectively.

Comet C/1996 B2 (Hyakutake)

On May 1, 1996, the spacecraft unexpectedly crossed the ion tail of Comet Hyakutake (C/1996 B2), revealing the tail to be at least 3.8 AU in length.

Comet C/1999 T1 (McNaught-Hartley)

Encounter with a comet tail happened again in 1999 when Ulysses flew through the ion tailings of C/1999 T1 (McNaught-Hartley). A coronal mass ejection carried the cometary material to Ulysses.

Solar southern polar regions

Between 2000 and 2001 it explored the southern solar polar regions, which gave many unexpected results. In particular the southern magnetic pole was found to be much more dynamic and without any fixed clear location. It is, of course, wrong to say that the Sun has no magnetic south pole. The Sun is not a magnetic monopole; the pole is merely more diffusely located than the north pole.

Jupiter

Ulysses approached aphelion in 2003/2004 and made further distant observations of Jupiter.

Comet C/2006 P1 (McNaught)

In 2007 Ulysses passed through the tail of comet C/2006 P1 (McNaught). The results were surprisingly different from its pass through Hyakutake's tail, with the measured solar wind velocity dropping from approximately 700 kilometers per second to less than 400 kilometers per second.

Extended mission

ESA's Science Programme Committee approved the fourth extension of the Ulysses mission to March 2009 thereby allowing it to operate over the Sun's poles for the third time in 2007 and 2008. After it became clear that the power output from the spacecraft's RTG would be insufficient to operate science instruments and keep the attitude control fuel, hydrazine, from freezing, instrument power sharing was initiated. Up until then, the most important instruments had been kept online constantly, whilst others were deactivated. When the probe neared the Sun, its power-hungry heaters were turned off and all instruments were turned on.

On February 22, 2008, 17 years 4 months after the launch of the spacecraft, ESA and NASA announced that mission operations for Ulysses would be likely to cease within a few months. On April 12, 2008 NASA announced that the end date will be July 1, 2008. The spacecraft operated successfully for over four times its design life. A component within the last remaining working chain of X-band downlink sub-system failed on January 15, 2008. The other chain in the X-band sub-system had previously failed in 2003.

Downlink to Earth resumed on S-band, but the beamwidth of the high gain antenna on S-band is not as narrow as on X – so the downlink signal was much weaker, thereby reducing the achievable data rate. As the spacecraft traveled on its outbound trajectory to the orbit of Jupiter, the downlink signal would have eventually fallen below the receiving capability of even the largest antennas (70m in diameter) of the Deep Space Network. Even before the downlink signal was lost due to distance, the hydrazine attitude control fuel on-board the spacecraft was considered likely to freeze, as the radioisotope thermal generators failed to generate enough power for the heaters to combat the cold of space. Once the hydrazine froze, the spacecraft would no longer be able to maneuver to keep its high gain antenna pointing towards Earth, and the downlink signal would then be lost in a matter of days. The failure of the X-band communications sub-system hastened this, because the coldest part of the fuel pipework was routed over the X-band TWTAs which, when one of them was operating, kept this part of the pipework sufficiently warm.

The previously announced mission end date of July 1, 2008 came and went but mission operations continued albeit in a reduced capacity. The availability of science data gathering was limited to only when Ulysses is in contact with a ground station due to the deteriorating S-band downlink margin no longer being able to support simultaneous real-time data and tape recorder playback. When the spacecraft was out of contact with a ground station, the S-band transmitter was switched off and the power was diverted to keep the internal heaters to add to the warming of the hydrazine. On June 30, 2009 ground controllers sent commands to switch to its low gain antennae which ceased communications with the spacecraft along with previous commands to schedule the shut down of its transmitter entirely.

Results

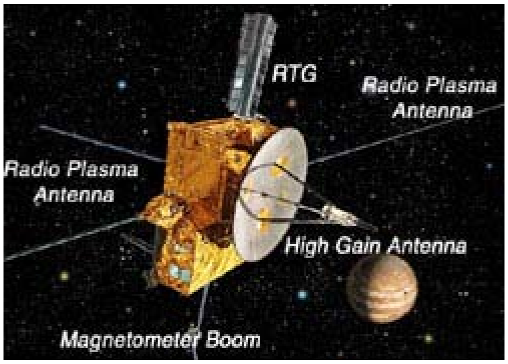
During cruise phases, *Ulysses* provided unique data. As the only spacecraft out of the ecliptic with a gamma-ray instrument, *Ulysses* was an important part of the InterPlanetary Network (IPN). The IPN detects gamma ray bursts (GRBs); since gamma rays cannot be focused with mirrors, it was very difficult to locate GRBs with enough accuracy to study them further. Instead, several spacecraft can locate the burst through triangulation (or, more specifically, multilateration). Each spacecraft has a gamma-ray detector, with readouts noted in tiny fractions of a second. By comparing the arrival times of gamma showers with the separations of the spacecraft, a location can be determined, for follow-up with other telescopes. Because gamma rays travel at the speed of light, wide separations are needed. Typically, a determination came from comparing: one of several spacecraft orbiting the Earth, an inner-Solar-system probe (to Mars, Venus, or an asteroid), and *Ulysses*. When *Ulysses* crossed the ecliptic twice per orbit, many GRB determinations lost accuracy.

Additional discoveries:

- *Ulysses* discovered that the Sun's magnetic field interacts with the Solar System in a more complex fashion than previously assumed.

- *Ulysses* discovered that dust coming into the Solar System from deep space was 30 times more abundant than previously expected.
- In 2007-2008 *Ulysses* determined that the magnetic field emanating from the Sun's poles is much weaker than previously observed.
- That the solar wind has "grown progressively weaker during the mission and is currently at its weakest since the start of the Space Age."

Spacecraft



Ulysses spacecraft

The spacecraft body is roughly a box, approximately 3.2 × 3.3 × 2.1 m in size. The box mounted the 1.65 m dish antenna and the RTG power source. The box was divided into noisy and quiet sections. The noisy section abutted the RTG; the quiet section housed the instrument electronics. Particularly "loud" components, such as the preamps for the radio dipole, were mounted outside the structure entirely, and the box acted as a Faraday cage.

Ulysses is spin-stabilised about its z-axis which roughly coincides with the axis of the dish antenna. The RTG, whip antennas, and instrument boom are placed to stabilize this axis. Spin is nominally 5 rpm. Inside the body is a hydrazine fuel tank. Hydrazine monopropellant was used for course corrections inbound to Jupiter, and is now used exclusively to repoint the spin axis (and thus, the antenna) at Earth. The spacecraft is controlled by eight thrusters, in two blocks. Thrusters are pulsed in the time domain to perform rotation or translation. Four Sun sensors detected orientation. For fine attitude control, the S-band antenna feed is mounted slightly off-axis. This offset feed combined with the spacecraft spin introduces an oscillation to an S-band radio signal transmitted from Earth when received on-board the spacecraft. The amplitude and phase of this oscillation is proportional to the oriention of the spin axis relative to the Earth direction. This method of determining the relative orientation is called CONSCAN and was widely employed in early infra-red guided missiles.

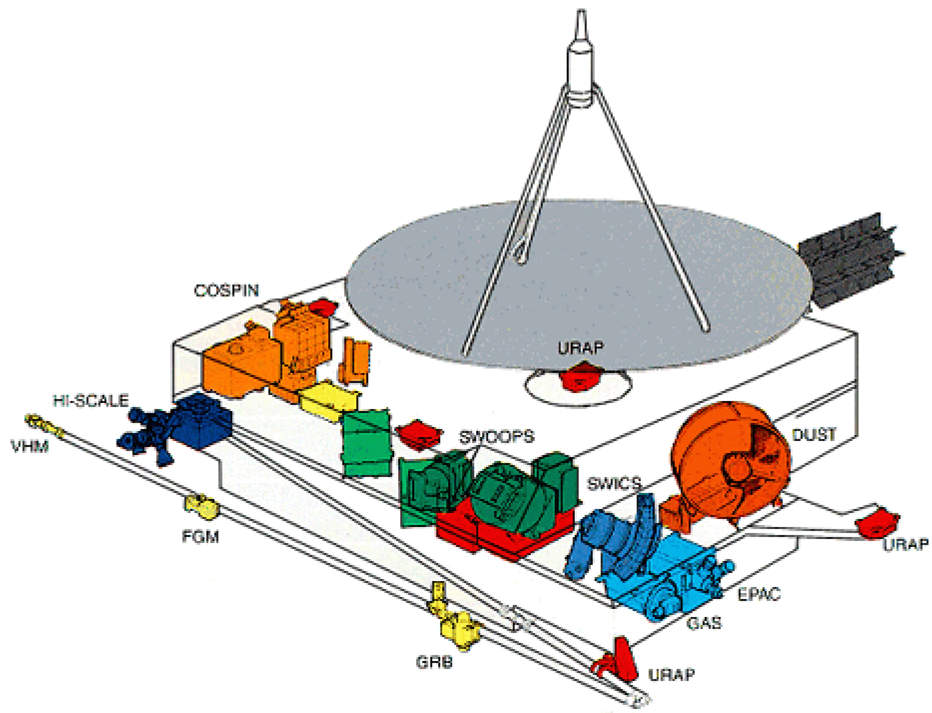
The spacecraft uses S-band for uplinked commands and downlinked telemetry, through dual redundant 5-watt transceivers. The spacecraft used X-band for science return (downlink only), using dual 20W TWTAs until the failure of the last remaining TWTA in January 2008. Both bands use the dish antenna with prime-focus feeds, unlike the Cassegrain feeds of most other spacecraft dishes.

Dual tape recorders, each of approximately 45 megabit capacity, store science data between the nominal 8-hour communications sessions during the prime and extended mission phases.

The spacecraft is designed to withstand both the heat of the inner Solar System and the cold at Jupiter distance. Extensive blanketing and electric heaters protect against cold.

Total mass at launch was 366.7 kg of which 33.5 kg was hydrazine (used for attitude control and orbit correction).

Instruments



Ulysses instruments

Ulysses radial boom test

Radio/Plasma antennas. Two beryllium-copper antennas unreeled outwards from the body, perpendicular to the RTG and spin axis. Together this dipole spanned 72 meters. A third antenna, of hollow beryllium-copper, deployed from the body, along the spin axis opposite the dish. It was a monopole antenna, 7.5 meters long. These measured radio waves generated by plasma releases, or the plasma itself as it passed over the spacecraft. This receiver ensemble was sensitive from dc to 1 MHz.

Experiment Boom. A third type of boom, shorter and much more rigid, extended from the last side of the spacecraft, opposite the RTG. This was a hollow carbon-fiber tube, of 50 mm diameter. It can be seen in the photo as the silver rod stowed alongside the body. It carried four types of instruments. A solid-state X-ray instrument, which was composed of two silicon detectors to study X-rays from solar flares and Jupiter's aurorae. The GRB experiment consisted of two CsI scintillator crystals with photomultipliers. Two different magnetometers were mounted: a vector helium magnetometer and a fluxgate magnetometer. A two axis magnetic search coil antenna measured AC magnetic fields.

Body-Mounted Instruments. Detectors for electrons, ions, neutral gas, dust, and cosmic rays were mounted on the spacecraft body around the quiet section.

SWOOPS (Solar Wind Observations Over the Poles of the Sun) measures positive ions and electrons.

Lastly, the radio communications link could be used to search for gravitational waves (through Doppler shifts) and to probe the Sun's atmosphere through occultation. No gravitational waves were detected.

Chapter- 2

Space and Solar System Exploration in 1992

Mars Observer

Mars Observer

Artist rendering of *Mars Observer* in orbit around Mars.

Operator	NASA / JPL
Major contractors	Astro Space
Mission type	Orbiter
Satellite of	Mars
Orbital insertion date	1993-08-24 *(planned)*
Launch date	1992-09-25 17:05:01 UTC (18 years, 3 months, and 21 days ago)
Launch vehicle	Titan III
Launch site	Space Launch Complex 40

	Cape Canaveral Air Force Station
Mission duration	(failure in transit) Last contact on day 331 1993-08-21 01:00 UTC
COSPAR ID	1992-063A
Homepage	Mars Observer Mission Profile
Mass	1,018 kg (2,244 lb)
Power	1147 W (Solar array / 2 NiCad batteries)

The **Mars Observer** spacecraft was a 1,018-kilogram (2,244 lb) robotic space probe launched by NASA on September 25, 1992 to study the Martian surface, atmosphere, climate and magnetic field. During the interplanetary cruise phase, communication with the spacecraft was lost on August 21, 1993, 3 days prior to orbital insertion. Attempts to re-establish communication with the spacecraft were unsuccessful.

Mission background

History

In 1984, a high priority mission to Mars was set forth by the Solar System Exploration Committee. Titled *Mars Observer*, the Martian orbiter was planned to expand on the vast information already gathered by the Viking program. Preliminary mission goals expected the probe to provide planetary magnetic field data, detection of certain spectral line signitures of minerals on the surface, images of the surface at 1 meter/pixel and global elevation data.

Mars Observer was originally planned to be launched in 1990 by a Space Shuttle Orbiter. The possibilty for an expendable rocket to be used was also suggested, if the spacecraft would be designed to meet certain constraints. On March 12th, 1987, the mission was rescheduled for launch in 1992, in leu of other backlogged missions (Galileo, Magellan, Ulysses). Along with a launch delay, budget overruns necessitated the elimination of two instruments to meet the 1992 planned launch. As the development matured, the primary science objectives were finalized as:

- Determine the global elemental and mineralogical character of the surface material.
- Define globally the topography and gravitational field.
- Establish the nature of the Martian magnetic field.
- Determine the temporal and spatial distribution, abundance, sources, and sinks of volatiles and dust over a seasonal cycle.

- Explore the structure and circulation of the atmosphere.

Spacecraft design

Mars Observer was based on previous satellites designed to orbit Earth (Satcom-K, DMSP, TIROS). The probe carried a scientific payload of 8 instruments that would provide data for 22 experiments during the mission.

Attitude control and propulsion

The spacecraft was constructed with four reaction wheels, 3-axis stabilization utilizing hydrazine monopropellant, a horizon sensor, a 6-slit star scanner, and five sun sensors. Combined, these systems would allow the space probe to maintain pointing of the high-gain antenna toward Earth autonomously.

Communications

The space probe included a 1.5-meter high-gain antenna mounted to a 6-meter boom to communicate with the Deep Space Network using the x-band.

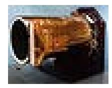
Power

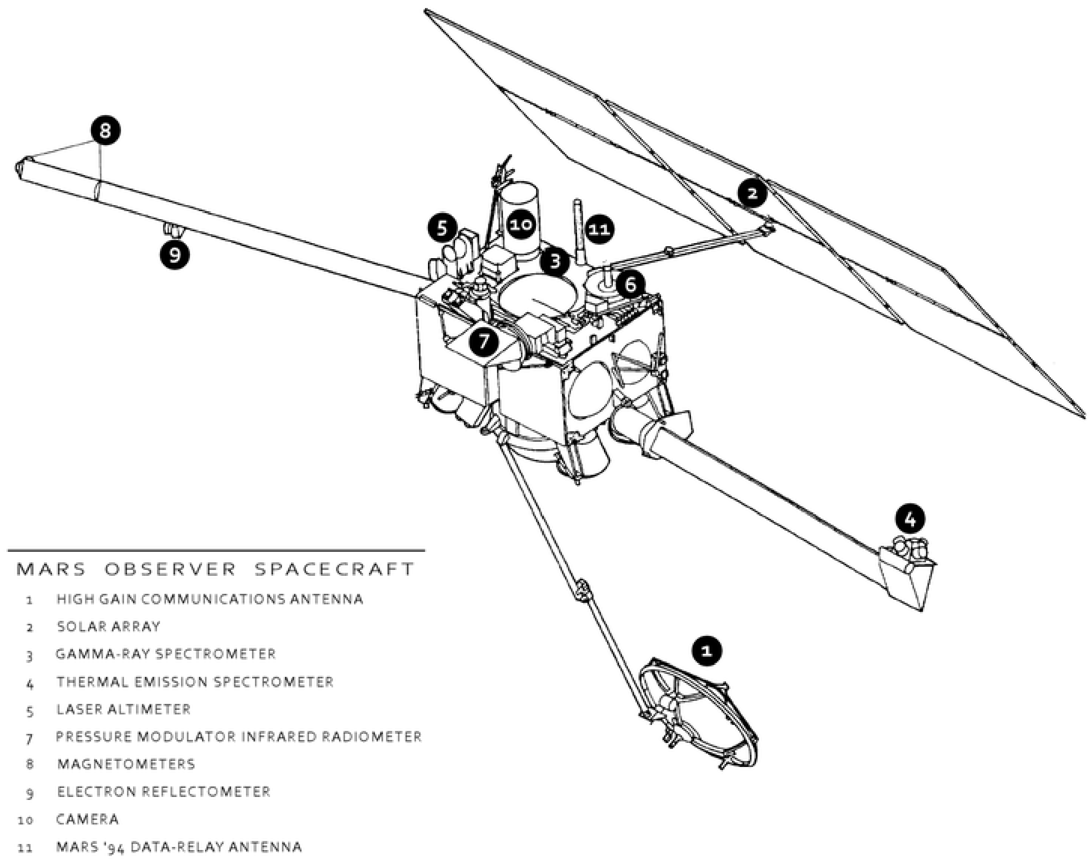
Power was supplied to the space probe through a 6-panel solar array, providing an average of 1147 W. When the solar array is deployed, it measures 7.0-meters x 3.7-meters. As the space probe would circle Mars, NiCad batteries would be used to power the space probe when in occultation of the sun and recharge while the solar array receives sun-light.

Scientific instruments

Instrument Name	Abr.	Image	Diagram	Description
Radio Science experiment	(**RS**)			Collects data on the gravity field and the Martian atmospheric structure with a special emphasis on temporal changes near the polar regions. **More** (relocated to **Mars Global Surveyor**)
Gamma Ray Spectrometer	(**GRS**)			Records the spectrum of gamma rays and neutrons emitted by the radioactive decay of elements contained in the Martian surface.

			More (relocated to **2001 Mars Odyssey**)
Magnetometer and Electron Reflectometer	**(MAG/ER)**		Uses the components of the on-board telecommunications system and the stations of the Deep Space Network to collect data on the nature of the magnetic field and interactions the field may have with solar wind. **More** (relocated to **Mars Global Surveyor**)
Mars Observer Laser Altimeter	**(MOLA)**	 	A laser altimeter used to define the topography of Mars. **More** (relocated to **Mars Global Surveyor**)
Pressure Modulator Infrared Radiometer	**(PMIRR)**		Utilizes narrow-band radiometric channels and two pressure modulation cells to measure atmospheric and surface emissions in the thermal infrared and a visible channel to measure dust particles and condensates in the atmosphere and on the surface at varying longitudes and seasons. **More** (relocated to **Mars Climate Orbiter**)
Thermal Emission Spectrometer	**(TES)**	 	Utilizes three sensors (Michelson interferometer, solar reflectance sensor, broadband radiance sensor) to measure thermal infrared emissions to map the mineral content of surface rocks, frosts and

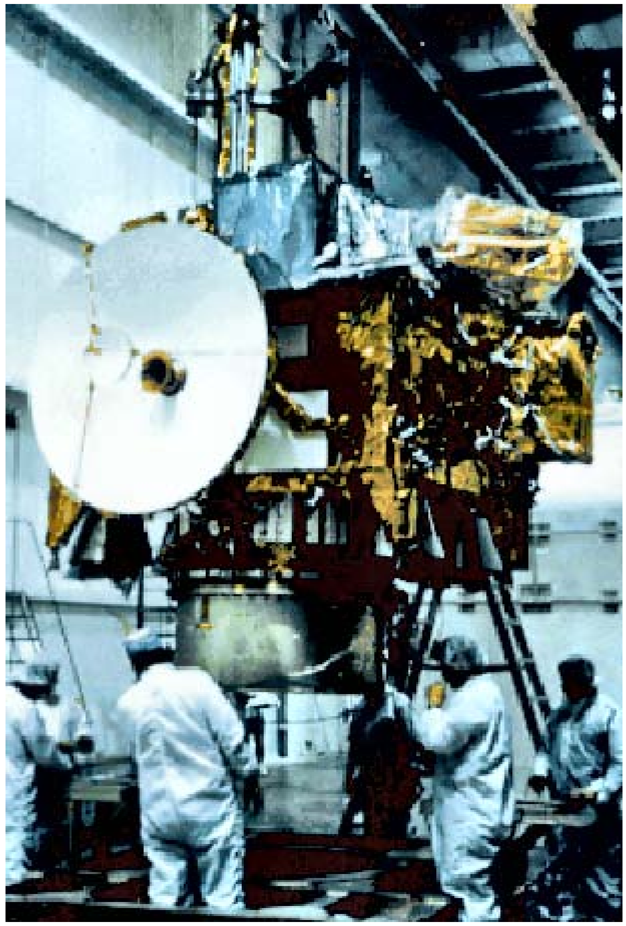
			the composition of clouds. **More** (relocated to **Mars Global Surveyor**)
Mars Observer Camera	(**MOC**)	 	Consists of narrow-angle and wide-angle telescopic cameras to study the meteorology/climatology and geoscience of Mars. **More** (relocated to **Mars Global Surveyor**)
Mars Balloon Relay	(**MBR**)		Planned as augmentation to return data from the penetrators and surface stations of the Russian Mars '94 mission and from penetrators, surface stations, a rover, and a balloon from the Mars '96 mission. **More** (relocated to **Mars Global Surveyor**)



Labeled diagram of *Mars Observer*

Mars Observer in the Payload Hazardous Servicing Facility

Technician assembling the *Mars Observer* space probe



Mars Observer in the clean room

Mission profile

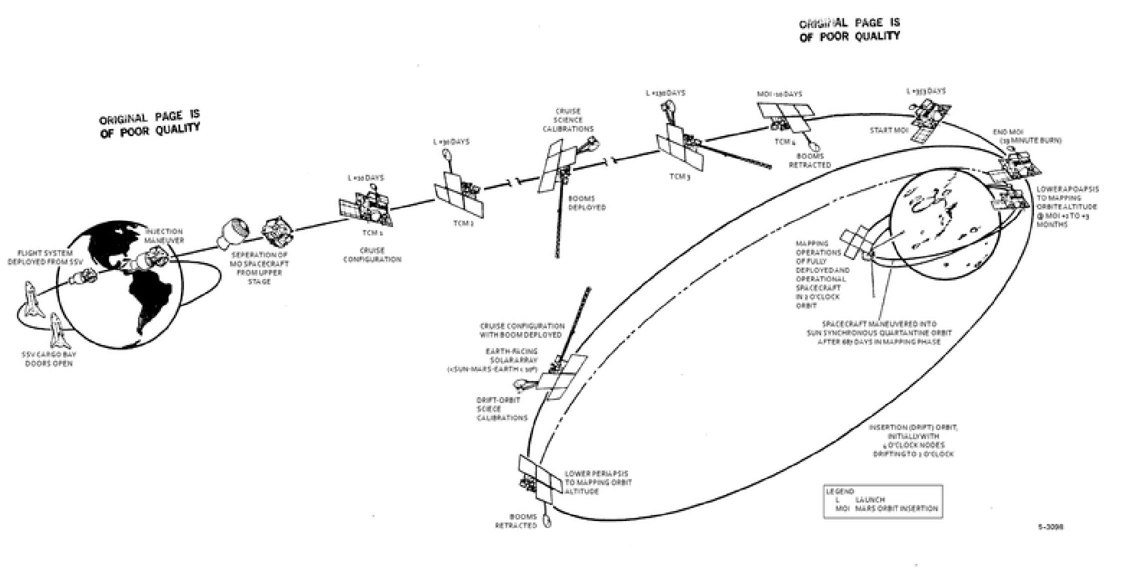
Titan III vehicle launching the *Mars Observer* spacecraft

Launch and trajectory

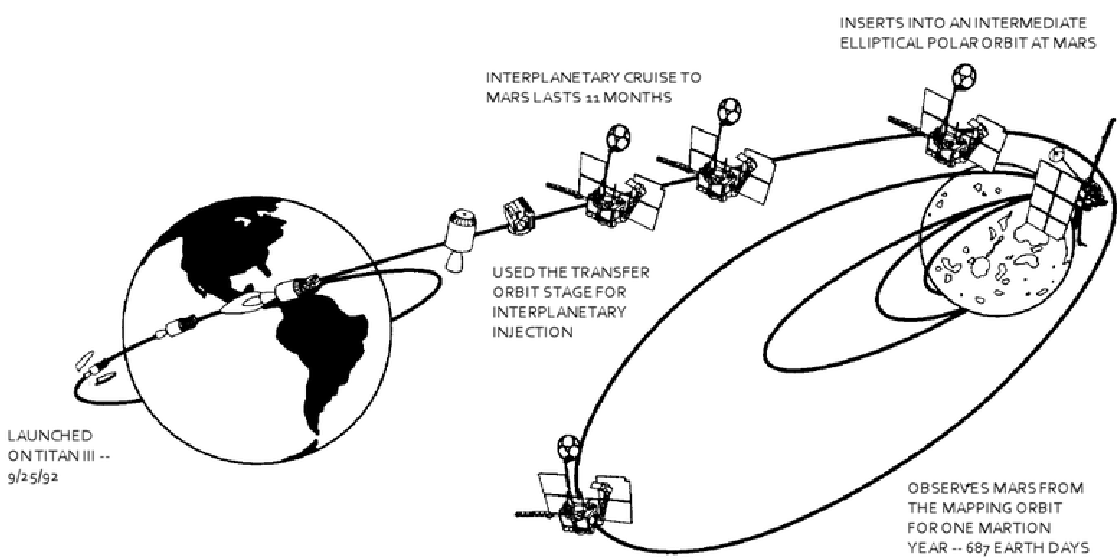
The *Mars Observer* probe was launched on September 25, 1992 at 17:05:01 UTC by the National Aeronautics and Space Administration from Space Launch Complex 40 at the Cape Canaveral Air Force Station in Florida, aboard a Commercial Titan III CT-4 launch vehicle.

Pre-launch complications

Prior to the spacecraft's launch, NASA found the Mars Observer to be "seriously contaminated with metal filings, paint chips and other trash" during a routine inspection. The spacecraft was subsequently removed from its Titan 34D rocket, and taken to a hangar for cleaning. The launch delay proved to be manageable, and the Observer launched from Cape Canaveral at 1:05 PM Eastern Daylight Time on September 25, 1992.

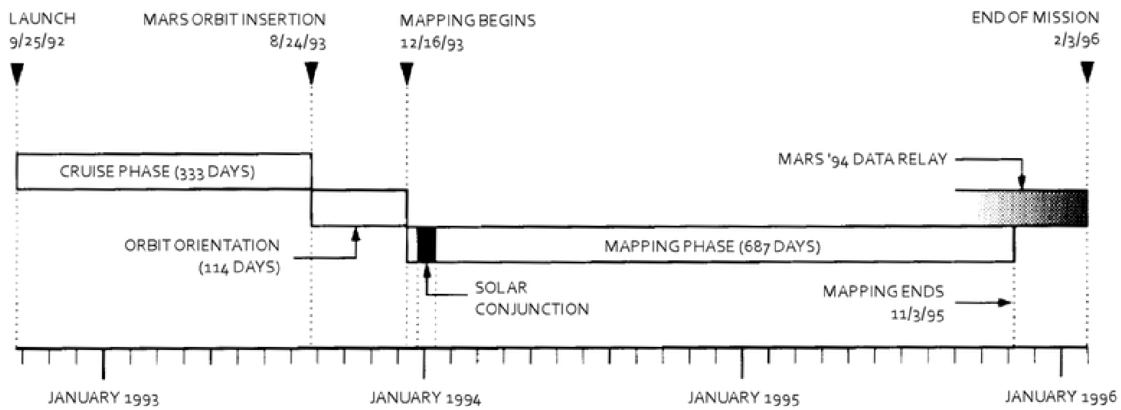


Original proposed trajectory of *Mars Observer* as launched from a Space Shuttle Orbiter



Launch trajectory of *Mars Observer* as launched from the Titan III launch vehicle

Timeline of travel



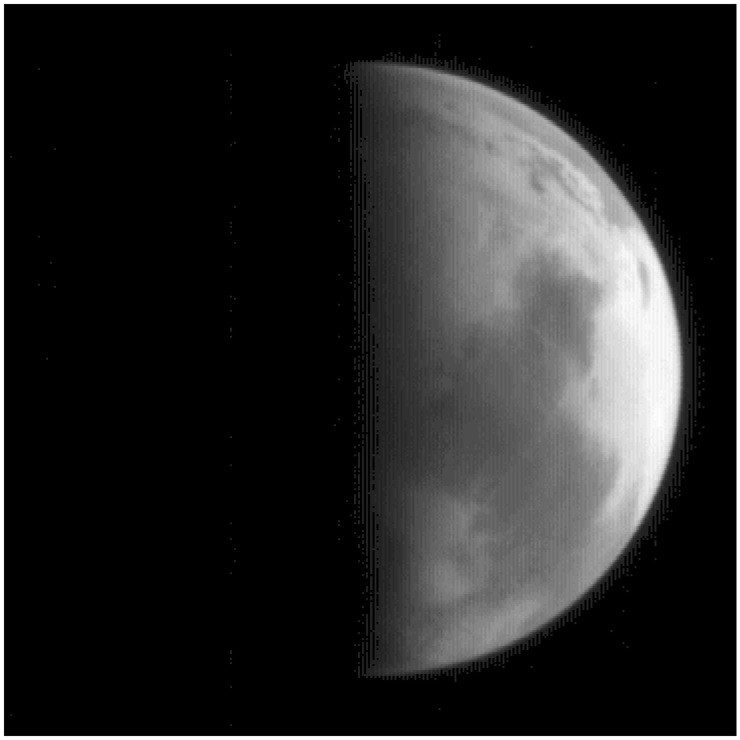
Anticipated timeline of the *Mars Observer* mission

Date	Event
1992-09-25	Spacecraft launched at 17:05:01 UTC
1993-08-21	Communication with spacecraft lost at 01:00 UTC.
1993-08-24	Planned Mars orbital insertion date.
1993-08-27	Mission declared a loss. No further attempts to contact.

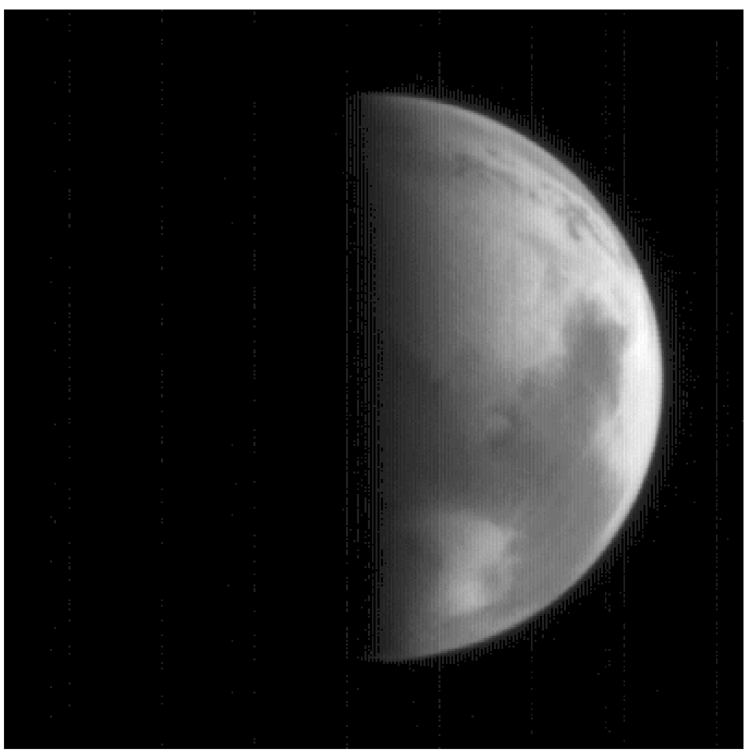
Encounter with Mars

Mars Observer was scheduled to perform a orbital insertion maneuver on August 24, 1993. However due to complications, contact with the spacecraft was lost on August 21, 1993. Although none of the primary objectives were achieved, the mission provided interplanetary cruise phase data, collected up to the date of last contact. This data would be useful for subsequent missions to Mars. Science instruments originally developed for *Mars Observer* were placed on three future orbiters to complete the mission objectives: **Mars Global Surveyor** launched in 1996, **Mars Climate Orbiter** launched in 1998 (*failure in transit*), **2001 Mars Odyssey** launched in 2001, **Mars Reconnaissance Orbiter** launched in 2005.

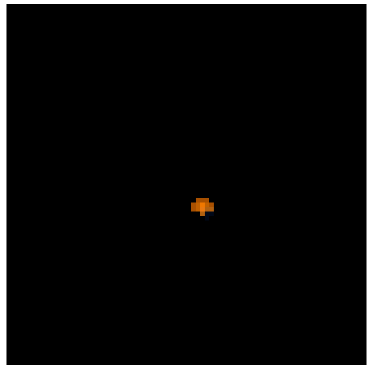
Jupiter as imaged by *MOC* en route to Mars



First image of Mars taken by *MOC* on July 27, 1993



Second *MOC* image of Mars, acquired one hour after the first



One of few wide-angle images by *Mars Observer* that were in color

Communications loss

On **August 21, 1993,** at 01:00 UTC, three days prior to the scheduled Mars orbital insertion, there was an "inexplicable" loss of contact with *Mars Observer*. New commands were sent every 20 minutes in the hopes that the spacecraft had drifted off course and could regain contact. However, the attempt was unsuccessful. It is unknown whether the spacecraft was able to follow its automatic programming and go into Mars orbit or if it flew by Mars and is now in a heliocentric orbit.

On **January 4, 1994,** an independent investigation board from the Naval Research Laboratory, announced their findings: the most probable cause in the loss of communication was a rupture of the fuel pressurization tank in the spacecraft's propulsion system. It is believed that hypergolic fuel may have leaked past valves in the system during the cruise to Mars, allowing the fuel and oxidizer to combine prematurely before reaching the combustion chamber. The leaking fuel and gas probably resulted in a high spin rate, causing the spacecraft to enter into the "contingency mode"; this interrupted the stored command sequence and did not turn the transmitter on. The engine was derived from one belonging to an Earth orbital satellite and was not designed to lie dormant for months before being fired.

Quoted from the report

"Because the telemetry transmitted from the Observer had been commanded off and subsequent efforts to locate or communicate with the spacecraft failed, the board was unable to find conclusive evidence pointing to a particular event that caused the loss of the Observer.

However, after conducting extensive analyses, the board reported that the most probable cause of the loss of communications with the spacecraft on Aug. 21, 1993, was a rupture of the fuel (monomethyl hydrazine (MMH)) pressurization side of the spacecraft's propulsion system, resulting in a pressurized leak of both helium gas and liquid MMH under the spacecraft's thermal blanket. The gas and liquid would most likely have leaked out from under the blanket in an unsymmetrical manner, resulting in a net spin rate. This high spin rate would cause the spacecraft to enter into the "contingency mode," which interrupted the stored command sequence and thus, did not turn the transmitter on.

Additionally, this high spin rate precluded proper orientation of the solar arrays, resulting in discharge of the batteries. However, the spin effect may be academic, because the released MMH would likely attack and damage critical electrical circuits within the spacecraft.

The board's study concluded that the propulsion system failure most probably was caused by the inadvertent mixing and the reaction of nitrogen tetroxide (NTO) and MMH within titanium pressurization tubing, during the helium pressurization of the fuel tanks. This reaction caused the tubing to rupture, resulting in helium and MMH being released from the tubing, thus forcing the spacecraft into a catastrophic spin and also damaging critical electrical circuits."

Chapter- 3

Space and Solar System Exploration in 1994

Clementine

Clementine

Organization	BMDO / NASA
Major contractors	Naval Research Laboratory
Mission type	Lunar science
Satellite of	Moon
Launch	January 25, 1994 at 16:34:00 UTC
Launch vehicle	Titan 23G
End of mission	Signal too weak to receive: June 1994
Mission duration	115 days
Mass	227 kg
NSSDC ID	1994-004A
Orbital elements	
Semimajor axis	5,116.0 km
Eccentricity	0.36
Inclination	90°
Orbital period	300 minutes
Apoapsis	4,594 km

Periapsis	2,162 km
Orbits	360
Instruments	
Charged particle telescope	Measure the flux and spectra of energetic protons and electrons
Ultraviolet/Visible camera	Study the Moon and 1620 Geographos at five different wavelengths in the ultraviolet spectrum
Near-Infrared CCD camera (NIR)	Study the Moon and 1620 Geographos at six different wavelengths in the near-infrared spectrum
Laser Image Detection and Ranging (LIDAR) system	Measure the distance from the spacecraft to a point on the surface of the Moon
High-resolution camera (HIRES)	Study selected portions of the Moon and asteroid

Clementine (officially called the **Deep Space Program Science Experiment** (DSPSE)) was a joint space project between the Ballistic Missile Defense Organization (BMDO, previously the Strategic Defense Initiative Organization, or SDIO) and NASA. Launched on January 25, 1994, the objective of the mission was to test sensors and spacecraft components under extended exposure to the space environment and to make scientific observations of the Moon and the near-Earth asteroid 1620 Geographos. The Geographos observations were not made due to a malfunction in the spacecraft.

The lunar observations made included imaging at various wavelengths in the visible as well as in ultraviolet and infrared, laser ranging altimetry, gravimetry, and charged particle measurements. These observations were for the purposes of obtaining multi-spectral imaging of the entire lunar surface, assessing the surface mineralogy of the Moon, obtaining altimetry from 60N to 60S latitude, and obtaining gravity data for the near side. There were also plans to image and determine the size, shape, rotational characteristics, surface properties, and cratering statistics of Geographos.

Clementine carried seven distinct experiments on-board: a UV/Visible Camera, a Near Infrared Camera, a Long Wavelength Infrared Camera, a High Resolution Camera, two Star Tracker Cameras, a Laser Altimeter, and a Charged Particle Telescope. The S-band transponder was used for communications, tracking, and the gravimetry experiment. The project was named Clementine after the song "Oh My Darling, Clementine" as the spacecraft would be "lost and gone forever" following its mission.

Spacecraft design

The spacecraft was an octagonal prism 1.88 m high and 1.14 m across with two solar panels protruding on opposite sides parallel to the axis of the prism. A 42-inch-diameter (1,100 mm) high-gain fixed dish antenna was at one end of the prism, and the 489 N thruster at the other end. The sensor openings were all located together on one of the eight panels, 90 degrees from the solar panels, and protected in flight by a single sensor cover.

The spacecraft propulsion system consisted of a monopropellant hydrazine system for attitude control and a bipropellant nitrogen tetroxide and monomethyl hydrazine system for the maneuvers in space. The bipropellant system had a total capability of about 1,900 m/s with about 550 m/s required for lunar insertion and 540 m/s for lunar departure.

Attitude control was achieved with 12 small attitude control jets, two star tracker cameras, and two inertial measurement units. The spacecraft was three-axis stabilized in lunar orbit via reaction wheels with a precision of 0.05 deg in control and 0.03 deg in knowledge. Power was provided by gimbaled, single axis, GaAs/Ge solar panels which charged a 15 A·h, 47 W·h/kg Nihau (Ni-H) common pressure vessel battery.

Spacecraft data processing was performed using a MIL-STD-1750A computer (1.7 MIPS) for savemode, attitude control, and housekeeping operations, a RISC 32-bit processor (18 MIPS) for image processing and autonomous operations, and an image compression system provided by the French Space Agency CNES. A data handling unit sequenced the cameras, operated the image compression system, and directed the data flow. Data was stored in a 2 Gbit dynamic solid state data recorder.

Mission

Clementine launch

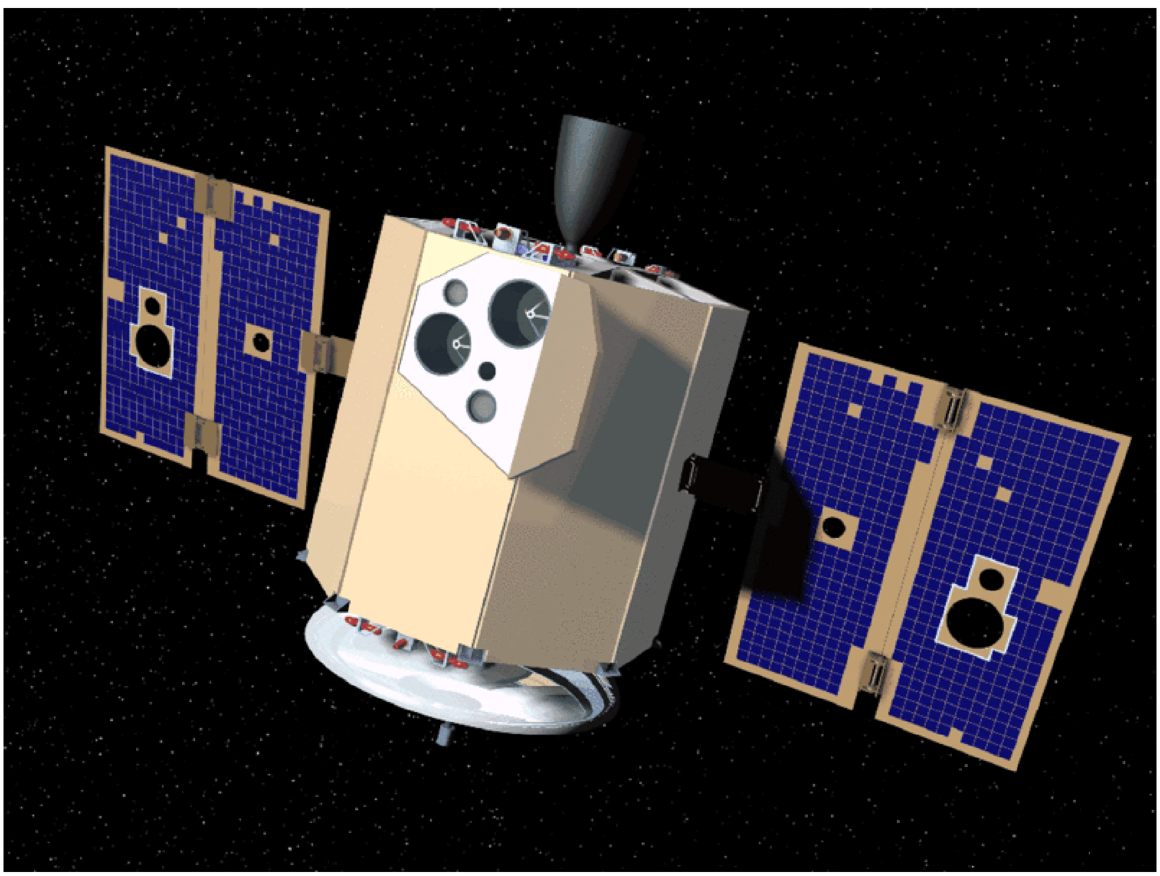
On January 25, 1994, Clementine was launched from Space Launch Complex 4 West at Vandenberg Air Force Base, California using a Titan II launch vehicle. The mission had two phases. After two Earth flybys, lunar insertion was achieved approximately one month after launch. Lunar mapping took place over approximately two months, in two parts. The first part consisted of a five hour elliptical polar orbit with a periapsis of about 400 km at 30 degrees south latitude and an apoapsis of 8300 km. Each orbit consisted of an 80 minute lunar mapping phase near periapsis and 139 minutes of downlink at apoapsis.

After one month of mapping the orbit was rotated to a periapsis at 30 degrees north latitude, where it remained for one more month. This allowed global imaging and altimetry coverage from 60° south to 60° north, over a total of 300 orbits.

After an Earth to moon transfer and two more Earth flybys, the spacecraft was to head for Geographos, arriving three months later for a flyby, with a nominal approach closer than 100 km. Unfortunately, on May 7, 1994, after the first Earth transfer orbit, a malfunction aboard the craft caused one of the attitude control thrusters to fire for 11 minutes, using up its fuel supply and causing Clementine to spin at 80 rpm. Under these conditions, the asteroid flyby could not yield useful results, so the spacecraft was put into a geocentric orbit passing through the Van Allen radiation belts to test the various components on board.

The mission ended in June 1994 when the power level onboard dropped to a point where the telemetry from the spacecraft was no longer intelligible.

NASA announced on March 5, 1998 that data obtained from Clementine indicated that there is enough water in polar craters of the moon to support a human colony and a rocket fueling station.



Artist's conception of Clementine fully deployed

Science instruments

Charged Particle Telescope (CPT)

The Charged Particle Telescope (CPT) on Clementine was designed to measure the flux and spectra of energetic protons (3–80 MeV) and electrons (25–500 KeV). The primary goals of the investigation were to: (1) study the interaction of the Earth's magnetotail and interplanetary shocks with the Moon; (2) monitor the solar wind in regions far removed from other spacecraft as part of a multimission coordinated study; and, (3) measure the effects of incident particles on the operating ability of the spacecraft solar cells and other sensors.

In order to meet the stringent limit on the mass of the instrument (<1 kg), it was implemented as a single element telescope. The telescope had a 10 degree half-angle field of view. The detector, a silicon surface-barrier type with an area of 100 mm^2 and a thickness of 3 mm, was shielded so as to prevent protons below 30 MeV from reaching it from directions other than via the aperture. The aperture was covered by a very thin foil to prevent light impinging on the detector and generating noise. The signal from the detector was broken up into nine channels, the lowest six dedicated to electron detection and the highest three to protons and heavier ions.

Ultraviolet/Visible camera

The Ultraviolet/Visible camera (UV/Vis) was designed to study the surfaces of the Moon and the asteroid Geographos at five different wavelengths in the ultraviolet and visible spectrum. The Geographos rendezvous was canceled due to equipment malfunction. This experiment yielded information on the petrologic properties of the surface material on the Moon, as well as giving images useful for morphologic studies and cratering statistics. Most images were taken at low Sun angles, which is useful for petrologic studies but not for observing morphology.

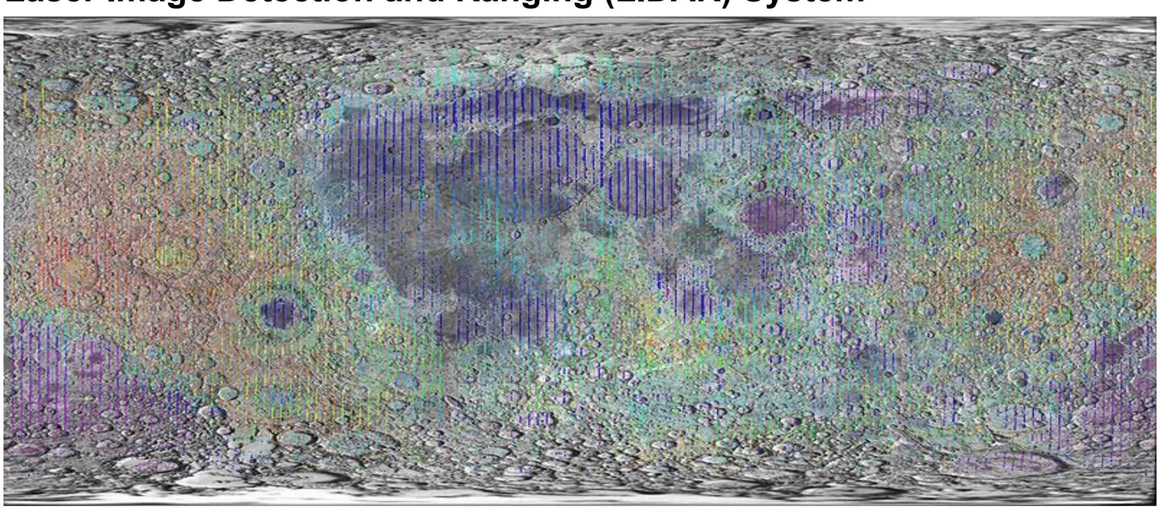
The sensor consisted of a catadioptric telescope with an aperture of 46 mm and fused silica lenses focused onto a coated Thompson CCD camera with a bandpass of 250–1000 nm and a six-position filter wheel. The wavelength response was limited on the short wavelength end by the transmission and optical blur of the lens, and on the long end by the CCD response. The CCD was a frame transfer device which allowed three gain states (150, 350, and 1000 electrons/bit). Integration times varied from 1–40 ms depending on gain state, solar illumination angle, and filter. The filter center wavelengths (and bandpass widths (FWHM)) were 415 nm (40 nm), 750 nm (10 nm), 900 nm (30 nm), 950 nm (30 nm), 1000 nm (30 nm), and a broad-band filter covering 400–950 nm. The field of view was 4.2 × 5.6 degrees, translating to a cross-track width of about 40 km at a nominal 400 km lunar altitude. The image array was 288 × 384 pixels. Pixel resolution varied from 100–325 m during a single orbit mapping run at the Moon. At Geographos the pixel resolution would have been 25 m at the 100 km closest approach, giving an image size about 7 × 10 km. The camera took twelve images in each 1.3 s image burst, which occurred 125 times over the 80-minute mapping span during each five-hour lunar orbit. The Moon's surface was covered completely during the two month lunar mapping phase of the mission. The dynamic range was 15,000. The signal-to-noise ratio varied from 25–87 depending on the surface albedo and phase angle, with a relative calibration of 1% and an absolute calibration of 15%.

Near-Infrared CCD Camera (NIR)

The Clementine Near-Infrared camera (NIR) was designed to study the surfaces of the Moon and the near-Earth asteroid 1620 Geographos at six different wavelengths in the near-infrared spectrum. This experiment yielded information on the petrology of the surface material on the Moon. The rendezvous with Geographos was canceled due to equipment malfunction.

The camera consisted of a catadioptric lens which focused on a mechanically cooled (to a temperature of 70 K) Amber InSb CCD focal-plane array with a bandpass of 1100–2800 nm and a six-position filter wheel. The filter center wavelengths (and bandpass widths (FWHM)) were: 1100 nm (60 nm), 1250 nm (60 nm), 1500 nm (60 nm), 2000 nm (60 nm), 2600 nm (60 nm), and 2780 nm (120 nm). The aperture was 29 mm with a focal length of 96 mm. The field of view was 5.6 × 5.6 degrees, giving a cross-track width of about 40 km at a nominal 400 km lunar altitude. The Moon had complete mapping coverage during the two month lunar phase of the mission. The image array is 256 × 256 pixels, and pixel resolution varied from 150–500 m during a single orbit mapping run at the Moon. (At Geographos the pixel resolution would have been 40 m at closest approach, giving an image size about 10 × 10 km.) The camera took twelve images in each 1.3 s image burst, which occurred 75 times over the 80 minute mapping span during each five hour lunar orbit. The dynamic range was 15,000. The signal-to-noise ratio varied from 11–97 depending on the surface albedo and phase angle, with a relative calibration of 1% and an absolute calibration of 30%. The gain varied from 0.5X to 36X.

Laser Image Detection and Ranging (LIDAR) System



Relief measurements made by LIDAR

The Clementine Laser Image Detection And Ranging (LIDAR) experiment was designed to measure the distance from the spacecraft to a point on the surface of the Moon. This will allow an altimetric map to be made, which can be used to constrain the morphology of large basins and other lunar features, study stress and strain and flexural properties of the lithosphere, and can be combined with gravity to study the density distribution in the crust. The experiment was also designed to measure distances to the surface of Geographos, but this phase of the mission was canceled due to a malfunction.

The LIDAR system consisted of a 180 mJ, 1064 nm wavelength Nd-YAG (Yttrium-Aluminum-Garnet) laser transmitter which transmitted pulses to the lunar surface. The laser produced a pulse with a width less than 10 ns. At 1064 nm wavelength, the pulse had an energy of 171 mJ with a divergence less than 500 microrad. At 532 nm, it had a 9 mJ pulse with a 4 millirad divergence. The reflected pulse travelled through the High-Resolution Camera telescope, where it was split off by a dichroic filter to a silicon avalanche photodiode detector. The detector was a single 0.5 × 0.5 mm cell SiAPD receiver with a field of view of 0.057 square degrees. The laser had a mass of 1250 g, the receiver was housed in the 1120 g HIRES camera. The travel time of a pulse gave the range to the surface. The LIDAR memory could save up to six return detections per laser firing, with a threshold set for the best compromise between missed detections and false alarms. The returns were stored in 39.972 m range bins, equal to the resolution of the 14-bit clock counter. The LIDAR has a nominal range of 500 km, but altimetric data was gathered for altitudes up to 640 km, which allowed coverage from 60 degrees south to 60 degrees north by the end of the lunar phase of the mission. The vertical resolution is 40 m, and the horizontal spot resolution is about 100 m. The across track spacing of the measurements at the equator was about 40 km. One measurement was made each second over a 45 minute period during each orbit, giving an along track spacing of 1–2 km.

High-Resolution Camera (HIRES)

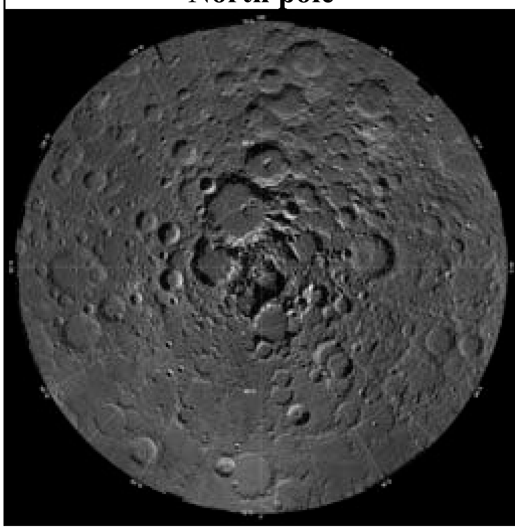
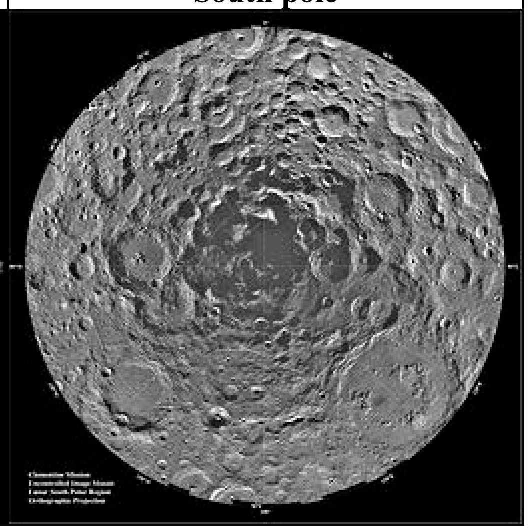
The Clementine High-Resolution Camera consisted of a telescope with an image intensifier and a frame-transfer CCD imager. The imaging system was designed to study selected portions of the surfaces of the Moon and the near-Earth asteroid 1620 Geographos, although the asteroid rendezvous was canceled due to a malfunction. This experiment allowed the detailed study of surface processes on the Moon and, combined with spectral data, allowed high-resolution compositional and geologic studies.

The imager was an intensified Thompson CCD camera with a six position filter wheel. The set of filters consisted of a broad-band filter with a bandpass of 400 to 800 nm, four narrow-band filters with center wavelengths (and bandpass width (FWHM)) of 415 nm (40 nm), 560 nm (10 nm), 650 nm (10 nm), and 750 nm (20 nm), and 1 opaque cover to protect the image intensifier. The field of view was 0.3 x 0.4 degrees, translating to a width of about 2 km at a nominal lunar altitude of 400 km. The image array is 288 × 384 pixels, (pixel size of 23 × 23 micrometers) so the pixel resolution at the Moon was 7–20 m depending on the spacecraft altitude. (At Geographos the resolution would have been <5 m at closest approach.) The clear aperture was 131 mm and the focal length was 1250 mm. The nominal imaging rate was about 10 frames per second in individual image bursts covering all filters at the Moon. The high resolution and small field of view only allowed coverage of selected areas of the Moon, in the form of either long, narrow strips of a single color or shorter strips of up to four colors. The instrument has a signal to noise ratio of 13 to 41 depending on the albedo and phase angle, with a 1% relative calibration and a 20% absolute calibration, and a dynamic range of 2000.

The telescope of the High-Resolution Camera was shared by the LIDAR instrument. The 1064 nm laser return was split to the LIDAR receiver (an avalanche photodiode detector) using a dichroic filter.

Imagery from the HIRES can be viewed in NASA World Wind software.

Polar regions (orthographic, centered on pole)

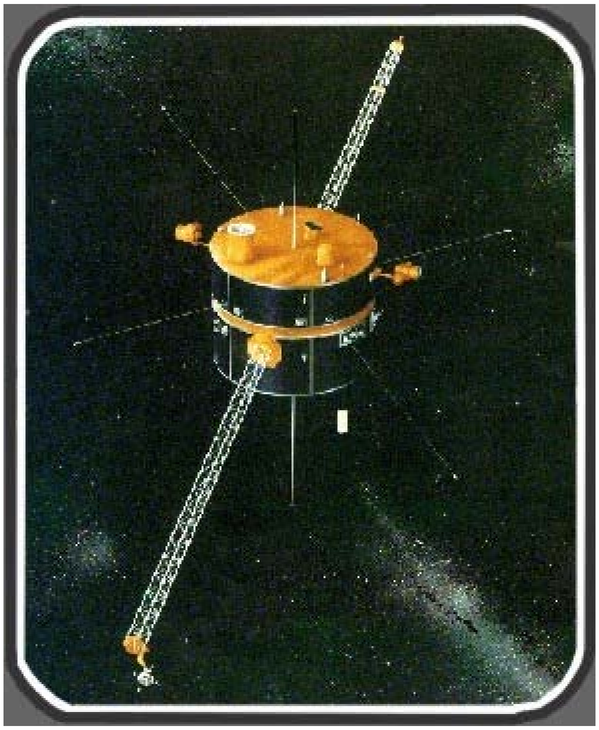
North pole	South pole
	

Bistatic Radar Experiment

The "Bistatic Radar Experiment", improvised during the mission, was designed to look for evidence of Lunar water at the Moon's poles. Radio signals from the Clementine probe's transmitter were directed towards the Moon’s north and south polar regions and their reflections detected by Deep Space Network receivers on Earth. Analysis of the magnitude and polarisation of the reflected signals suggested the presence of volatile ices, interpreted as including water ice, in the Moon's surface soils. A possible ice deposit equivalent to a sizeable lake was announced. However, later studies made using the Arecibo radio telescope showed similar reflection patterns even from areas not in permanent shadow (and in which such volatiles cannot persist), leading to suggestions that Clementine’s results had been misinterpreted and may have been due to other factors such as surface roughness.

WIND (spacecraft)

WIND



The first of NASA's Global Geospace Science (GGS) program.

Operator	NASA
Major contractors	Martin Marietta
Mission type	Space probe
Orbital insertion date	2004
Orbits	L_1 Lagrangian point
Launch date	04:31:00 EST 1994-11-01
Launch vehicle	Delta II
Launch site	Pad 17B Cape Canaveral Air Force Station
Mission duration	Minimum: 3 year

Mass	Dry: 895 kg Propellant: 300 kg

The Global Geospace Science (GGS) **WIND** satellite is a NASA science spacecraft launched at 04:31:00 EST on November 1, 1994 from launch pad 17B at Cape Canaveral Air Force Station (CCAFS) in Merritt Island, Florida aboard a McDonnell Douglas Delta II 7925-10 rocket. WIND was designed and manufactured by Martin Marietta Astro Space Division in East Windsor, New Jersey. The satellite is a spin stabilized cylindrical satellite with a diameter of 2.4 m and a height of 1.8 m.

It was deployed to study radio and plasma that occur in the solar wind and in the Earth's magnetosphere before the solar wind reaches the Earth. The spacecraft's original mission was to orbit the Sun at the L_1 Lagrangian point, but this was delayed when the SOHO and ACE spacecraft were sent to the same location. WIND has been at L_1 continuously since 2004, and is still operating as of April 2008.

Mission Operations are conducted from the WIND/POLAR Mission Operations Room (MOR) in Building 3 at Goddard Space Flight Center in Greenbelt, Maryland.

WIND is the sister ship to GGS Polar.

The science objectives of the WIND mission

- Provide complete plasma, energetic particle, and magnetic field input for magnetospheric and ionospheric studies.
- Determine the magnetospheric output to interplanetary space in the up-stream region.
- Investigate basic plasma processes occurring in the near-Earth solar wind.
- Provide baseline ecliptic plane observations to be used in heliospheric latitudes from ULYSSES.

Other Names

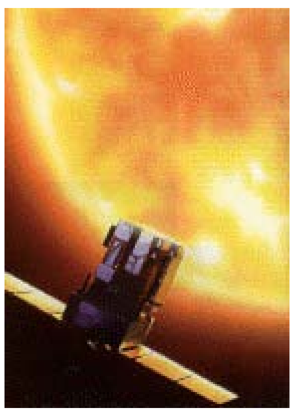
- GGS/Wind
- ISTP/Wind
- Wind/GGS
- Wind/ISTP
- Interplanetary Physics Laboratory (IPL)
- NORAD Satellite Catalog Number: 23333
- NSSDC International Designator: 1994-071A

Chapter- 4

Space and Solar System Exploration in 1995

Solar and Heliospheric Observatory

Solar and Heliospheric Observatory (SOHO)



General information

NSSDC ID	1995-065A
Organization	ESA / NASA
Launch date	December 2, 1995
Launch vehicle	Atlas IIAS
Mission length	15 years, 3 months, and 12 days elapsed
Mass	1,850 kg (610 kg payload)
Orbit height	1.5×10^{6} km (heliocentric)
Orbit period	1 Earth year
Location	L1

Wavelength	optical through UV, also magnetic information
	Instruments
GOLF	solar core oscillations (Doppler-sensitive photometer)
VIRGO	core oscillations (photometric imager)
MDI	oscillations and magnetic fields (Doppler imager)
SUMER	coronal physics (UV spectrograph)
CDS	corona/chromosphere physics (UV spectrograph)
EIT	low corona and photosphere (UV telescope)
UVCS	solar wind acceleration (UV spectrograph)
LASCO	low to outer corona (two visible light cameras, one imaging Fabry-Pérot interferometer)
SWAN	solar wind density (UV camera)
CELIAS **COSTEP** **ERNE**	solar wind ions (material samplers)

The **Solar and Heliospheric Observatory** (**SOHO**) is a spacecraft built by a European industrial consortium led by Matra Marconi Space (now Astrium) that was launched on a Lockheed Martin Atlas IIAS launch vehicle on December 2, 1995 to study the Sun, and has discovered 2000 comets. It began normal operations in May 1996. It is a joint project of international cooperation between the European Space Agency (ESA) and NASA. Originally planned as a two-year mission, *SOHO* currently continues to operate after over ten years in space. In October 2009, a mission extension lasting until December 2012 was approved.

In addition to its scientific mission, it is currently the main source of near-real time solar data for space weather prediction. Along with the GGS Wind and Advanced Composition Explorer (*ACE*), *SOHO* is one of three spacecraft currently in the vicinity of the Earth-Sun L1 point, a point of gravitational balance located approximately 0.99 astronomical unit (AU)s from the Sun and 0.01 AU from the Earth. In addition to its scientific contributions, *SOHO* is distinguished by being the first three-axis-stabilized spacecraft to use its reaction wheels as a kind of virtual gyroscope; the technique was adopted after an on-board emergency in 1998 that nearly resulted in the loss of the spacecraft.

Orbit

The 610 kg *SOHO* spacecraft is in a halo orbit around the Sun-Earth L1 point, the point between the Earth and the Sun where the balance of the (larger) Sun's gravity and the (smaller) Earth's gravity is equal to the centripetal force needed for an object to have the same orbital period in its orbit around the Sun as the Earth, with the result that the object will stay in that relative position.

Although sometimes described as being at L_1, the *SOHO* spacecraft is not exactly at L_1 as this would make communication difficult due to radio interference generated by the Sun, and because this would not be a stable orbit. Rather it lies in the (constantly moving) plane which passes through L_1 and is perpendicular to the line connecting the sun and the Earth. It stays in this plane, tracing out an elliptical lissajous orbit centered about L_1. It orbits L_1 once every six months, while L_1 itself orbits the sun every 12 months as it is coupled with the motion of the Earth. This keeps *SOHO* at a good position for communication with Earth at all times.

Communication with Earth

In normal operation the spacecraft transmits a continuous 200 kbit/s data stream of photographs and other measurements via the NASA Deep Space Network of ground stations. *SOHO'*s data about solar activity are used to predict solar flares, so electrical grids and satellites can be protected from their damaging effects (mainly, solar flares may produce geomagnetic storms, which in turn produce geomagnetically induced current creating black-outs, etc.).

In 2003 ESA reported the failure of the antenna Y-axis stepper motor, necessary for pointing the high gain antenna and allowing the downlink of high rate data. At the time, it was thought that the antenna anomaly might cause two to three week data-blackouts every three months. However, ESA and NASA engineers managed to use *SOHO*'s low gain antennas together with the larger 34 and 70 meter DSN ground stations and judicious use of *SOHO*'s Solid State Recorder (SSR) to prevent total data loss, with only a slightly reduced data flow every three months.

Near Loss of SOHO

The SOHO Mission Interruption sequence of events began on June 24, 1998, while the SOHO Team was conducting a series of spacecraft gyroscope calibrations and maneuvers. Operations proceeded until 23:16 UTC when SOHO lost lock on the Sun, and entered an emergency attitude control mode called Emergency Sun Reacquisition (ESR). The SOHO Team attempted to recover the observatory, but SOHO entered the emergency mode again on June 25 02:35 UTC. Recovery efforts continued, but SOHO entered the emergency mode for the last time at 04:38 UTC. All contact with SOHO was lost, and the mission interruption had begun. SOHO was spinning, losing electrical power, and no longer pointing at the Sun.

Expert ESA personnel were immediately dispatched from Europe to the United States to direct operations. Days passed without contact from SOHO. On July 23, the Arecibo Observatory and DSN antennas were used to locate SOHO with radar, and to determine its location and attitude. SOHO was close to its predicted position, oriented with its side versus the usual front Optical Surface Reflector panel pointing toward the Sun, and was rotating at one RPM. Once SOHO was located, plans for contacting SOHO were formed. On August 3 a carrier was detected from SOHO, the first signal since June 25. After days of charging the battery, a successful attempt was made to modulate the carrier and downlink telemetry on August 8. After instrument temperatures were downlinked on August 9, data analysis was performed, and planning for the SOHO recovery began in earnest.

The SOHO Recovery Team began by allocating the limited electrical power. After this, SOHO's anomalous orientation in space was determined. Thawing the frozen hydrazine fuel tank using SOHO's thermal control heaters began on August 12. Thawing pipes and the thrusters was next, and SOHO was re-oriented towards the Sun on September 16. After nearly a week of spacecraft bus recovery activities and an orbital correction maneuver, the SOHO spacecraft (bus) returned to normal mode on September 25 at 19:52 UTC. Recovery of the instruments began on October 5 with SUMER, and ended on October 24, 1998 with CELIAS.

Only one gyro remained operational after this recovery, and on December 21 that gyro failed. Attitude control was accomplished with manual thruster firings that consumed 7 kg of fuel weekly, while ESA developed a new gyroless operations mode that was successfully implemented on February 1, 1999.

Scientific Objectives

The three main scientific objectives of *SOHO* are:

- Investigation of the outer layer of the Sun, which consists of the chromosphere, transition region, and the corona. CDS, EIT, LASCO, SUMER, SWAN, and UVCS are used for this solar atmosphere remote sensing.

- Making observations of solar wind and associated phenomena in the vicinity of L_1. CELIAS and CEPAC are used for "in situ" solar wind observations.
- Probing the interior structure of the Sun. GOLF, MDI, and VIRGO are used for helioseismology.

Instruments

The *SOHO* Payload Module (PLM) consists of twelve instruments, each capable of independent or coordinated observation of the Sun or parts of the Sun, and some spacecraft components. The instruments are:

- **Coronal Diagnostic Spectrometer (CDS)** which measures density, temperature and flows in the corona.
- **Charge ELement and Isotope Analysis System (CELIAS)** which studies the ion composition of the solar wind.
- **Comprehensive SupraThermal and Energetic Particle analyser collaboration (COSTEP)** which studies the ion and electron composition of the solar wind. COSTEP and ENRE are sometimes referred to together as the COSTEP-ERNE Particle Analyzer Collaboration (CEPAC).
- **Extreme ultraviolet Imaging Telescope (EIT)** which studies the low coronal structure and activity.
- **Energetic and Relativistic Nuclei and Electron experiment (ERNE)** which studies the ion and electron composition of the solar wind.
- **Global Oscillations at Low Frequencies (GOLF)** which measures velocity variations of the whole solar disk to explore the core of the sun.
- **Large Angle and Spectrometric COronagraph experiment (LASCO)** which studies the structure and evolution of the corona by creating an artificial solar eclipse.
- **Michelson Doppler Imager (MDI)** which measures velocity and magnetic fields in the photosphere to learn about the convection zone which forms the outer layer of the interior of the sun and about the magnetic fields which control the structure of the corona. The MDI is the biggest producer of data by far on *SOHO*. In fact, two of SOHO's virtual channels are named after MDI, VC2 (MDI-M) carries MDI magnetogram data, and VC3 (MDI-H) carries MDI Helioseismology data.
- **Solar Ultraviolet Measurement of Emitted Radiation (SUMER)** which measures plasma flows, temperature and density in the corona.
- **Solar Wind ANisotropies (SWAN)** which uses telescopes sensitive to a characteristic wavelength of hydrogen to measure the solar wind mass flux, map the density of the heliosphere, and observe the large-scale structure of the solar wind streams.
- **UltraViolet Coronagraph Spectrometer (UVCS)** which measures density and temperature in the corona.
- **Variability of solar IRradiance and Gravity Oscillations (VIRGO)** which measures oscillations and solar constant both of the whole solar disk and at low resolution, again exploring the core of the sun.

Observations from some of the instruments can be formatted as images, most of which are also readily available on the internet for either public or research use. Others such as spectra and measurements of particles in the solar wind do not lend themselves so readily to this. These images range in wavelength or frequency from optical (Hα) to extreme ultraviolet (UV). Images taken partly or exclusively with non-visible wavelengths are shown on the *SOHO* page and elsewhere in false color. Unlike many space-based and ground telescopes, there is no time formally allocated by the SOHO program for observing proposals on individual instruments: interested parties can contact the instrument teams directly via e-mail and the SOHO web site to request time via that instrument team's internal processes (some of which are quite informal, provided that the ongoing reference observations are not disturbed). A formal process (the "JOP" program) does exist for using multiple SOHO instruments collaboratively on a single observation. JOP proposals are reviewed at the quarterly Science Working Team ("SWT") meetings, and JOP time is allocated at monthly meetings of the Science Planning Working Group.

As a consequence of its observing the Sun, *SOHO* (specifically the LASCO instrument) has inadvertently allowed the discovery of comets by blocking out the Sun's glare. Approximately one-half of all known comets have been spotted by *SOHO*, discovered over the last 15 years by over 70 people representing 18 different countries searching through the publicly available SOHO images online. Michał Kusiak of the Polish Jagiellonian University (Uniwersytet Jagielloński) discovered SOHO's 1999th and 2000th comets on 26 December 2010.

Instrument contributors

The Max Planck Institute for Solar System Research contributed to SUMER, LASCO and CELIAS instruments. The Smithsonian Astrophysical Observatory built the UVCS instrument. The Lockheed Martin Solar and Astrophysics Laboratory (LMSAL) built the MDI instrument in collaboration with the solar group at Stanford University.

Chapter- 5

Space and Solar System Exploration in 1996

NEAR Shoemaker

Artist's conception of the NEAR Shoemaker spacecraft

Flyby of	253 Mathilde
Satellite of	433 Eros
Orbital insertion date	2000-02-14 at 433 Eros
Orbits	230 orbits of 433 Eros
Launch date	20:43:27 UTC 1996-02-17
Launch vehicle	Booster: Delta 7925-8 Upper Stage: Star 48
Launch site	Cape Canaveral Air Force Station

Orbital decay	Never - landed on 433 Eros 2001-02-12
COSPAR ID	1996-008A
Mass	Launch: ~800 kg On orbit dry: 487 kg
Power	Instruments: 81 w Total: 1800 w

The **Near Earth Asteroid Rendezvous - Shoemaker** (NEAR Shoemaker), renamed after its 1996 launch in honor of planetary scientist Eugene M. Shoemaker, is a robotic space probe designed by NASA to study the near-Earth asteroid Eros from close orbit over a period of a year. The mission succeeded in closing in with the asteroid and orbited several times around it, finally terminating by touching down on the asteroid on 12 February 2001.

The primary scientific objective of NEAR was to return data on the bulk properties, composition, mineralogy, morphology, internal mass distribution and magnetic field of Eros. Secondary objectives include studies of regolith properties, interactions with the solar wind, possible current activity as indicated by dust or gas, and the asteroid spin state. This data will be used to help understand the characteristics of asteroids in general, their relationship to meteorites and comets, and the conditions in the early solar system. To accomplish these goals, the spacecraft was equipped with an X-ray/gamma ray spectrometer, a near-infrared imaging spectrograph, a multi-spectral camera fitted with a CCD imaging detector, a laser rangefinder, and a magnetometer. A radio science experiment was also performed using the NEAR tracking system to estimate the gravity field of the asteroid. The total mass of the instruments was 56 kg, and they required 81 W power.

Mission profile

- Launch date/time: 1996-02-17 at 20:43:27 UTC
- On-orbit dry mass: 487 kg
- Nominal power output: 1800 W

Summary

Near-Earth asteroid Eros as seen from the NEAR spacecraft

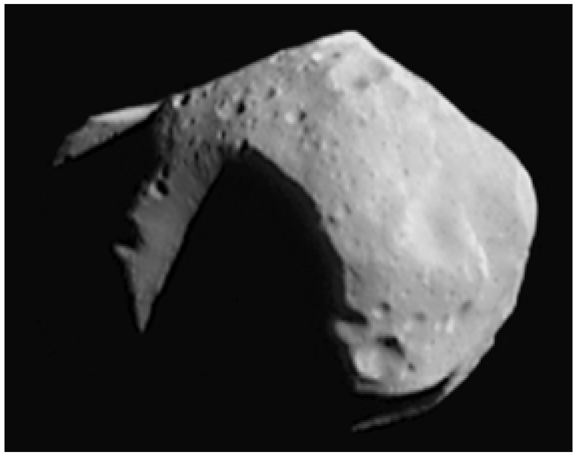
The primary goal of the mission was to study the near Earth asteroid 433 Eros from orbit for approximately one year. Eros is an S-type asteroid approximately 13 × 13 × 33 km in size, the second largest near-Earth asteroid. Initially the orbit was circular with a radius of 200 km. The radius of the orbit was brought down in stages to a 50 × 50 km orbit on 30 April 2000 and decreased to 35 × 35 km on July 14, 2000. The orbit was raised over succeeding months to a 200 × 200 km orbit and then slowly decreased and altered to a 35 × 35 km retrograde orbit on December 13, 2000. The mission ended with a touchdown in the "saddle" region of Eros on February 12, 2001.

Some scientists claim that the ultimate goal of the mission was to link Eros, an asteroidal body, to meteorites recovered on Earth. With sufficient data on chemical composition, a causal link could be established between Eros and other S-type asteroids, and those meteorites believed to be pieces of S-type asteroids (perhaps Eros itself). Once this connection is established, meteorite material can be studied with large, complex, and evolving equipment, and the results extrapolated to bodies in space. NEAR-Shoemaker did not prove or disprove this link to the satisfaction of scientists. However, it is undeniable that NEAR data advanced the field of asteroidal studies tremendously.

The journey to Eros

Launch of the NEAR spacecraft, February 1996

After launch on a Delta 7925-8 (a Delta II launch vehicle with nine strap-on solid-rocket boosters and a Star 48 (PAM-D) third stage) and exit from Earth orbit, NEAR entered the first part of its cruise phase. NEAR spent most of the cruise phase in a minimal activity "hibernation" state, which ended a few days before the flyby of the 61 km diameter asteroid 253 Mathilde.



One of the images from the flyby of 253 Mathilde

On June 27, 1997 the spacecraft flew within 1200 km of Mathilde at 12:56 UT at 9.93 km/s, returning imaging and other instrument data. The flyby produced over 500 images which covered 60% of Mathilde's surface, as well as gravitational data allowing calculations of Mathilde's dimensions and mass.

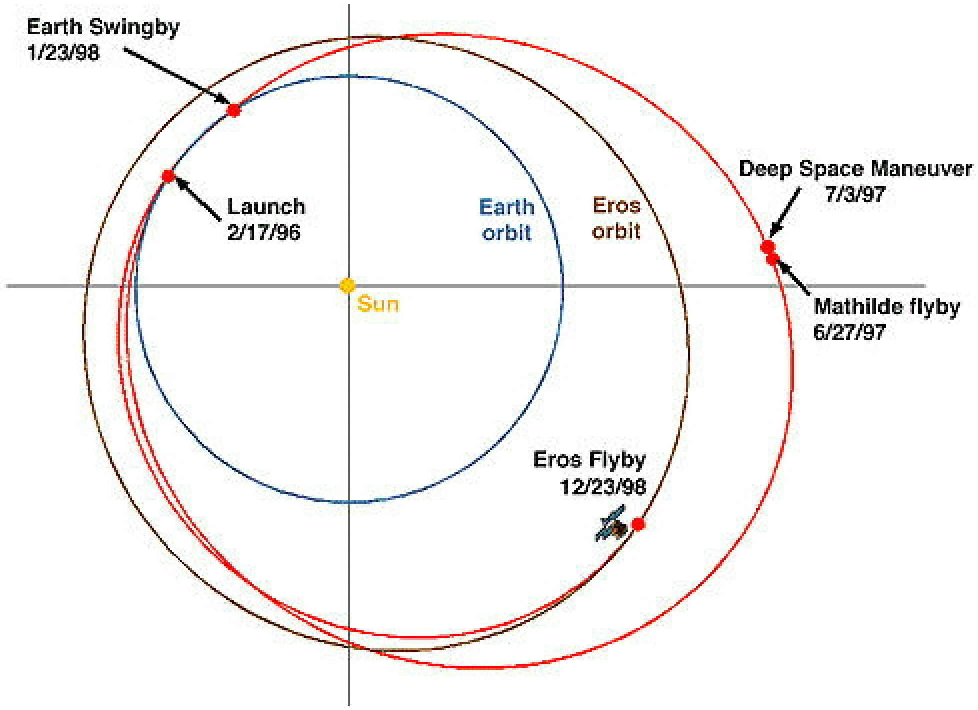
On July 3, 1997 NEAR executed the first major deep space maneuver, a two-part burn of the main 450 N thruster. This decreased the velocity by 279 m/s and lowered perihelion from 0.99 AU to 0.95 AU. The Earth gravity assist swingby occurred on January 23, 1998 at 7:23 UT. The closest approach was 540 km, altering the orbital inclination from 0.5 to 10.2 degrees, and the aphelion distance from 2.17 to 1.77 AU, nearly matching those of Eros. Instrumentation was active at this time.

Failure of first attempt at orbital insertion

The first of four scheduled rendezvous burns was attempted on December 20, 1998 at 22:00 UT. The burn sequence was initiated but immediately aborted. The spacecraft subsequently entered safe mode and began tumbling. The spacecraft's thrusters were fired thousands of times during the anomaly which expended 29 kg of propellant reducing the program's propellant margin to zero. This anomaly almost resulted in the complete loss of the spacecraft due to the loss of solar orientation and subsequent battery drain. Contact between the spacecraft and mission control was not re-established for over 24 hours. The full root cause has not been determined but software programming errors and operational errors contributed to the severity of the anomaly.

The original mission plan called for the four burns to be followed by an orbit insertion burn on January 10, 1999, but the abort of the first burn and loss of communication made this impossible. A new plan was put into effect in which NEAR flew by Eros on December 23, 1998 at 18:41:23 UT at a speed of 965 m/s and a distance of 3827 km from the center of mass of Eros. Images of Eros were taken by the camera, data were collected by the near IR spectrograph, and radio tracking was performed during the flyby. A rendezvous maneuver was performed on January 3, 1999 involving a thruster burn to match NEAR's orbital speed to that of Eros. A hydrazine thruster burn took place on January 20 to fine-tune the trajectory. On August 12 a two-minute thruster burn slowed the spacecraft velocity relative to Eros to 300 km/h.

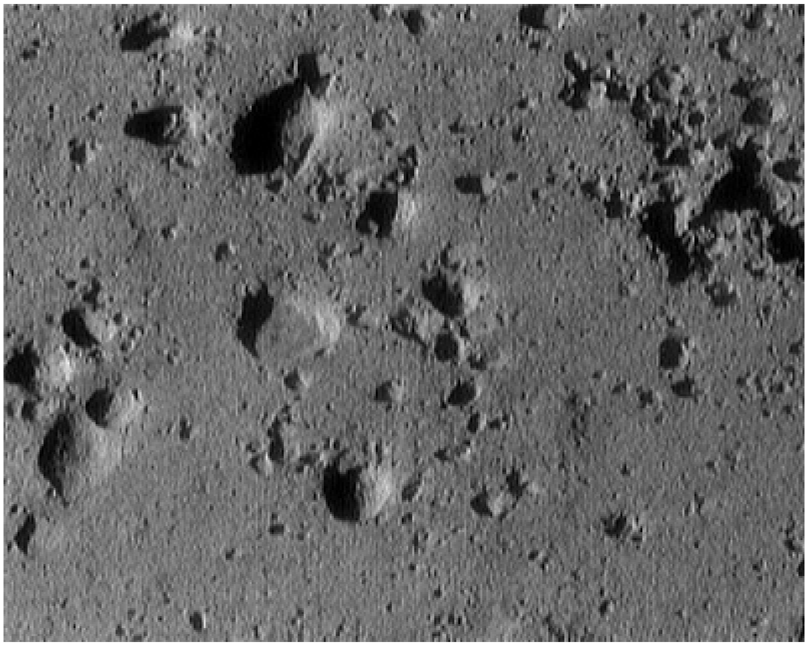
Orbital insertion



Trajectory graphic depicting the voyage of the NEAR spacecraft

Orbital insertion around Eros occurred on 14 February 2000 at 15:33 UT (10:33 AM EST) after NEAR completed a 13 month heliocentric orbit which closely matched the orbit of Eros. A rendezvous maneuver was completed on February 3 at 17:00 UT, slowing the spacecraft from 19.3 to 8.1 m/s relative to Eros. Another maneuver took place on February 8 increasing the relative velocity slightly to 9.9 m/s. Searches for satellites of Eros took place on January 28, and 4 and 9 February, none were found. The scans were for scientific purposes and to mitigate any chances of collision with a satellite. NEAR went into a 321 x 366 km orbit around Eros on February 14. The orbit was slowly decreased to a 35 km circular polar orbit by July 14. NEAR remained in this orbit for 10 days and then was backed out in stages to a 100 km circular orbit by September 5, 2000. Maneuvers in mid-October led to a flyby of Eros within 5.3 km of the surface at 07:00 UT on 26 October.

Orbits and landing

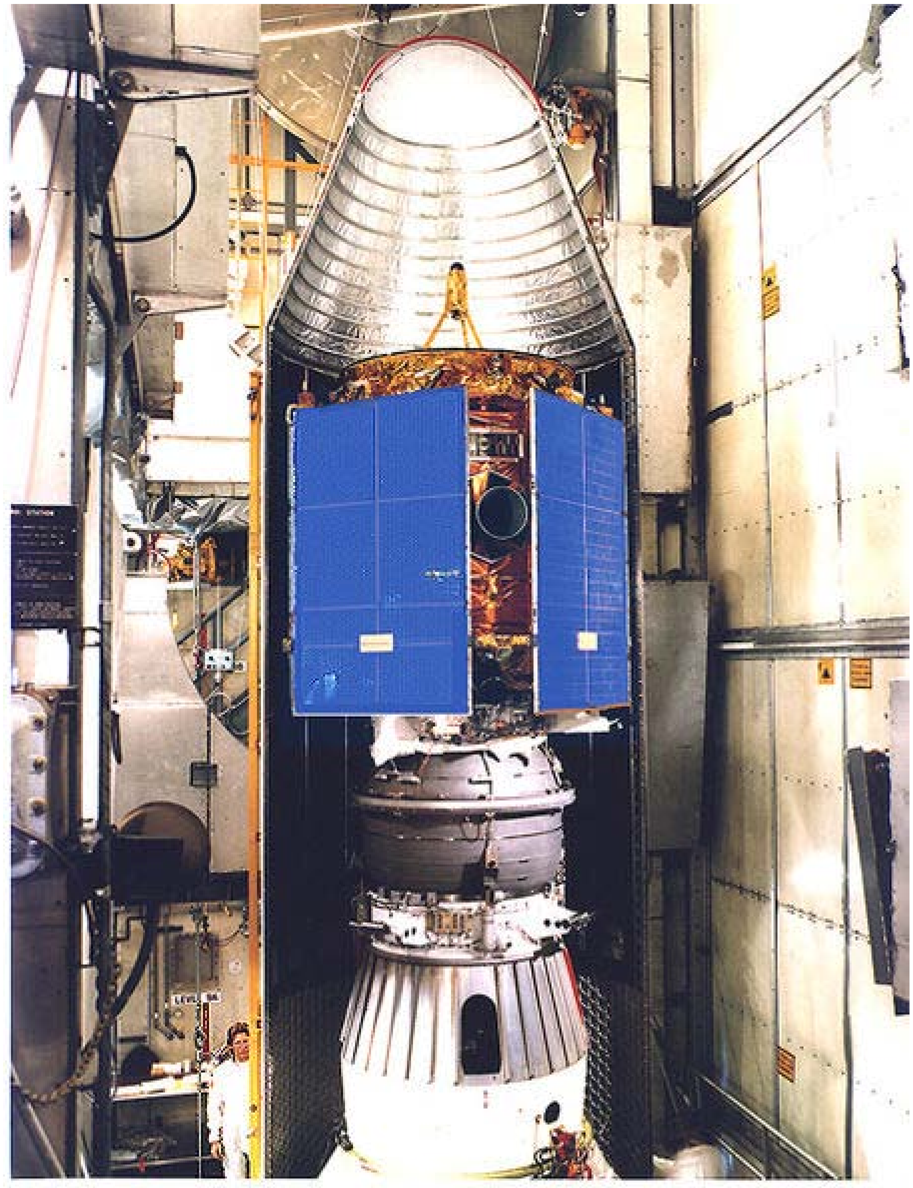


Eros asteroid from approximately 1,150 meters (area in image is roughly 54 meters wide). This image was taken during NEAR's descent to the surface of the asteroid.

Following the flyby NEAR moved to a 200 km circular orbit and shifted the orbit from prograde near-polar to a retrograde near-equatorial orbit. By December 13, 2000 the orbit was shifted back to a circular 35 km low orbit. Starting on January 24, 2001 the spacecraft began a series of close passes (5 to 6 km) to the surface and on January 28 passed 2 to 3 km from the asteroid. The spacecraft then made a slow controlled descent to the surface of Eros ending with a touchdown just to the south of the saddle-shaped feature Himeros on February 12, 2001 at approximately 20:01 UT (3:01 p.m. EST). To the surprise of the controllers, the spacecraft was undamaged and operational after the landing at an estimated speed of 1.5 to 1.8 meters per second (thus becoming the first spacecraft to soft-land on an asteroid). After receiving an extension of antenna time on the Deep Space Network, the spacecraft's gamma-ray spectrometer was reprogrammed to collect data on Eros' composition from a vantage point about four inches from the surface where it was ten times more sensitive than when it was used in orbit.

At 7 p.m. EST on February 28, 2001 the last data signals were received from NEAR Shoemaker before it was shut down. A final attempt to communicate with the spacecraft on December 10, 2002 was unsuccessful.

Spacecraft and subsystems



NEAR spacecraft inside its Delta II rocket

The spacecraft has the shape of an octagonal prism, approximately 1.7 m on a side, with four fixed gallium arsenide solar panels in a windmill arrangement, a fixed 1.5 m X-band high-gain radio antenna with a magnetometer mounted on the antenna feed, and an X-ray solar monitor on one end (the forward deck), with the other instruments fixed on the opposite end (the aft deck). Most electronics are mounted on the inside of the decks. The propulsion module is contained in the interior.

The craft is three-axis stabilized and uses a single bipropellant (hydrazine / nitrogen tetroxide) 450 newton (N) main thruster, and four 21 N and seven 3.5 N hydrazine thrusters for propulsion, for a total delta-V potential of 1450 m/s. Attitude control is achieved using the hydrazine thrusters and four reaction wheels. The propulsion system carries 209 kg of hydrazine and 109 kg of NTO oxidizer in two oxidizer and three fuel tanks.

Power is provided by four 1.8 by 1.2 meter gallium arsenide solar panels which can produce 400 watts at 2.2 AU (329,000,000 km), NEAR's maximum distance from the Sun, and 1800 W at one AU (150,000,000 km). Power is stored in a nine ampere-hour, 22-cell rechargeable super nickel-cadmium battery.

Spacecraft guidance is achieved through the use of a sensor suite of five digital solar attitude detectors, an inertial measurement unit, (IMU) and a star tracker camera pointed opposite the instrument pointing direction. The IMU contains hemispherical resonator gyroscopes and accelerometers. Four reaction wheels (arranged so that any three can provide complete three-axis control) are used for normal attitude control. The thrusters are used to dump angular momentum from the reaction wheels, as well as for rapid slew and propulsive maneuvers. Attitude control is to 0.1 degree, line-of-sight pointing stability is within 50 microradians over one second, and post-processing attitude knowledge is to 50 microradians.

The command and data handling subsystem is composed of two redundant command and telemetry processors and solid state recorders, a power switching unit, and an interface to two redundant 1553 standard data buses for communications with other subsystems. The solid state recorders are constructed from 16 Mbit IBM Luna-C DRAMs. One recorder has 1.1 gigabits of storage, the other has 0.67 gigabits.

The NEAR mission was the first launch of NASA's Discovery Program, a series of small-scale spacecraft designed to proceed from development to flight in under three years for a cost of less than $150 million. The construction, launch, and 30 day cost for this mission is estimated at $122 million. The final total mission cost was $224 million which consisted of $124.9 million for spacecraft development, $44.6 million for launch support and tracking, and $54.6 million for mission operations and data analysis.

Mars Global Surveyor

Mars Global Surveyor

Artist's conception of *Mars Global Surveyor*

Operator	NASA
Major contractors	Orbiter
Satellite of	Mars
Orbital insertion date	1997-09-12 01:17:00 UTC
Launch date	1996-11-07 17:00:50 UTC (14 years, 2 months, and 9 days ago)
Launch vehicle	Delta 7925
Mission duration	April 1, 1999 - November 2, 2006 (lost communication) Primary mission *(completed 2001-01-31)* First extended mission

	(completed 2002-01-31) Second extended mission *(completed 2002-12-31)* Comm Relay mission *(completed 2006-09-30)* Relay entended mission *(completed 2006-11-02)*
COSPAR ID	1996-062A
Homepage	Mars Global Surveyor
Mass	1,030.5 kg (2,272 lb)
Power	980 W (Solar array / 2 NiH_2 batteries)
Orbital elements	
Eccentricity	.7126
Inclination	93°
Apoapsis	17,836 km (11,083 mi)
Periapsis	171.4 km (107 mi)
Orbital period	11.64 h

The ***Mars Global Surveyor*** (***MGS***) was a US spacecraft developed by NASA's Jet Propulsion Laboratory and launched November 1996. It began the United States's return to Mars after a 10-year absence. It completed its primary mission in January 2001 and was in its third extended mission phase when, on 2 November 2006, the spacecraft failed to respond to messages and commands. A faint signal was detected three days later which indicated that the craft had gone into safe mode. All attempts to recontact the Mars Global Surveyor and resolve the problem failed. In January 2007 NASA officially ended the mission.

Specifications

The *Surveyor* spacecraft, fabricated at the Lockheed Martin Astronautics plant in Denver, is a rectangular-shaped box with wing-like projections (solar panels) extending from opposite sides. When fully loaded with propellant at the time of launch, the spacecraft weighed 1,060 kg (2,337 lb). Most of *Surveyor*'s mass lies in the box-shaped module occupying the center portion of the spacecraft. This center module is made of two smaller rectangular modules stacked on top of each other, one of which is called the equipment module and holds the spacecraft's electronics, science instruments, and the 1750A mission computer. The other module, called the propulsion module, houses *Surveyor'*s rocket engines and propellant tanks.

Scientific instruments

Five scientific instruments fly onboard *Mars Global Surveyor*:

- **MOC** - the Mars Orbiter Camera, operated by Malin Space Science Systems
- **MOLA** - the Mars Orbiter Laser Altimeter
- **TES** - the Thermal Emission Spectrometer
- **MAG/ER** - a Magnetometer and electron reflectometer
- **USO/RS** Ultrastable Oscillator for Doppler measurements
- **MR** Mars Relay - Signal receiver

The Mars Orbiter Camera (MOC) science investigation used 3 instruments: a narrow angle camera that took (black-and-white) high resolution images (usually 1.5 to 12 m per pixel) and red and blue wide angle pictures for context (240 m per pixel) and daily global imaging (7.5 km per pixel). MOC returned more than 240,000 images spanning portions of 4.8 Martian years, from September 1997 and November 2006. A high resolution image from MOC is either 1.5 or 3.1 km wide. So any image from this camera is at most 3.1 km wide. Often, a picture will be smaller than this because it has been cut to just show a certain feature. These high resolution images may be 3 to 10 km long. When a high resolution image is taken, a context image is taken as well. The context image shows the image footprint of the high resolution picture. Context images are typically 115.2 km square with 240 m/pixel resolution.

Launch and orbit insertion

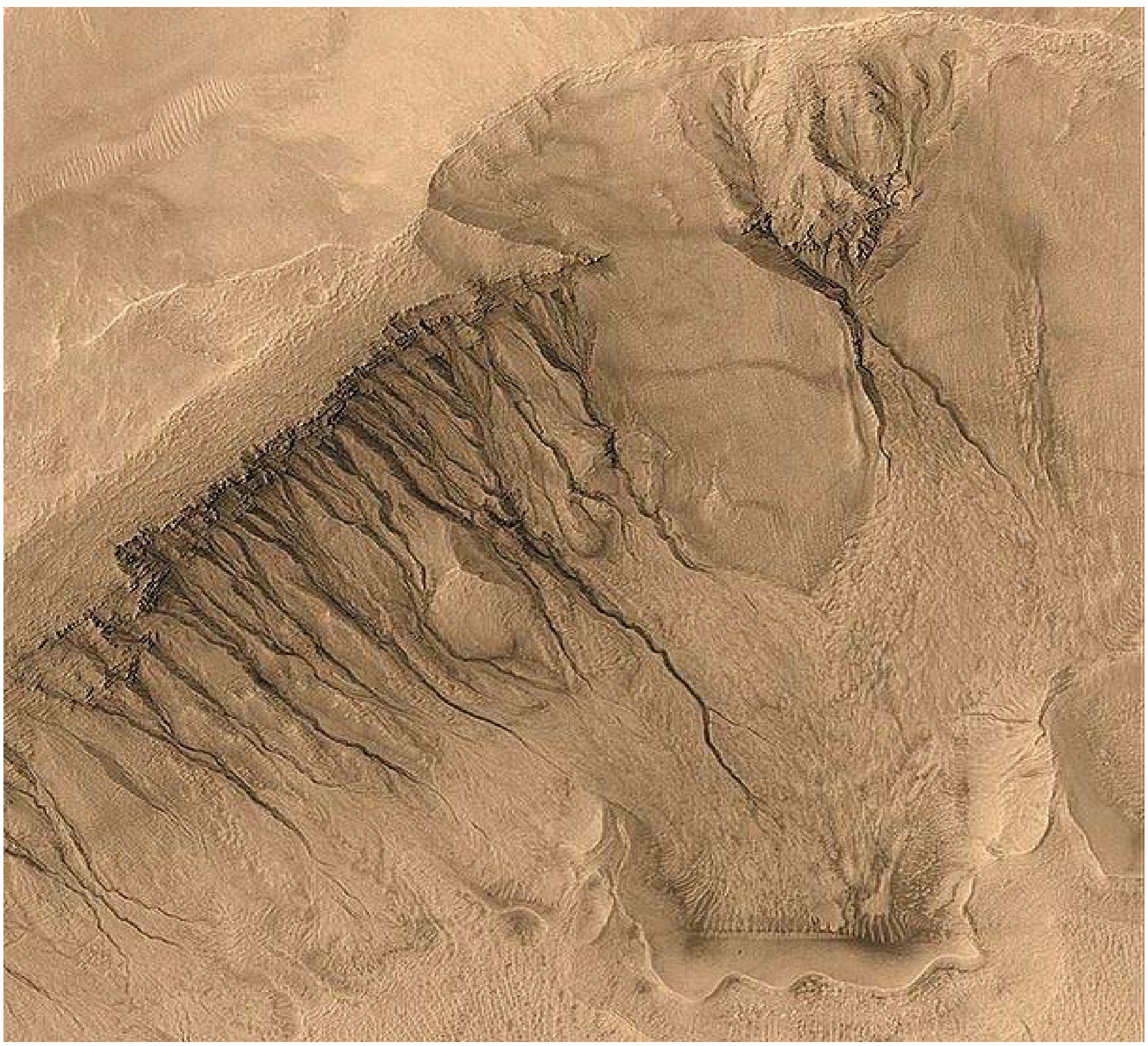
The *Surveyor* spacecraft was launched from the Cape Canaveral Air Station in Florida on 7 November 1996 aboard a Delta II rocket. The spacecraft traveled nearly 750 million kilometers (466 million miles) over the course of a 300-day cruise to reach Mars on 11 September 1997.

Upon reaching Mars, *Surveyor* fired its main rocket engine for the 22-minute Mars orbit insertion (MOI) burn. This maneuver slowed the spacecraft and allowed the planet's gravity to capture it into orbit. Initially, Surveyor entered a highly elliptical orbit that took 45 hours to complete. The orbit had a periapsis of 262 km (163 mi) above the northern hemisphere, and an apoapsis of 54,026 km (33,570 mi) above the southern hemisphere.

Aerobraking

After orbit insertion, *Surveyor* performed a series of orbit changes to lower the periapsis of its orbit into the upper fringes of the Martian atmosphere at an altitude of about 110 km (68 mi). During every atmospheric pass, the spacecraft slowed down by a slight amount because of atmospheric resistance. The density of the Martian atmosphere at such altitudes is comparatively low, allowing this procedure to be performed without damage to the spacecraft. This slowing caused the spacecraft to lose altitude on its next pass through the orbit's apoapsis. Surveyor used this aerobraking technique over a period of four months to lower the high point of its orbit from 54,000 km (33,554 mi) to altitudes near 450 km (280 mi).

On 11 October, the flight team performed a maneuver to raise the periapsis out of the atmosphere. This suspension of aerobraking was performed because air pressure from the atmosphere caused one of *Surveyor'*s two solar panels to bend backward by a slight amount. The panel in question was slightly damaged shortly after launch in November 1996. Aerobraking was resumed on 7 November after flight team members concluded that aerobraking was safe, provided that it occurs at a more gentle pace than proposed by the original mission plan.



This image taken by *Mars Global Surveyor* spans a region about 1,500 m (4,921 ft) across, showing gullies on the walls of Newton Basin in Sirenum Terra. Similar channels on Earth are formed by flowing water, but on Mars the temperature is normally too cold and the atmosphere too thin to sustain liquid water. Nevertheless, many scientists hypothesize that liquid groundwater can sometimes surface on Mars, erode gullies and channels, and pool at the bottom before freezing and evaporating.

Under the new mission plan, aerobraking occurred with the low point of the orbit at an average altitude of 120 km (75 mi), as opposed to the original altitude of 110 km (68 mi). This slightly higher altitude resulted in a decrease of 66 percent in terms of air resistance pressure experienced by the spacecraft. During these six months, aerobraking reduced the orbit period to between 12 and 6 hours.

From May to November 1998, aerobraking was temporarily suspended to allow the orbit to drift into the proper position with respect to the Sun. Without this hiatus, 'Surveyor' would complete aerobraking with its orbit in the wrong solar orientation. In order to maximize the efficiency of the mission, these six months were devoted to collecting as much science data as possible. Data was collected between two to four times per day, at the low point of each orbit.

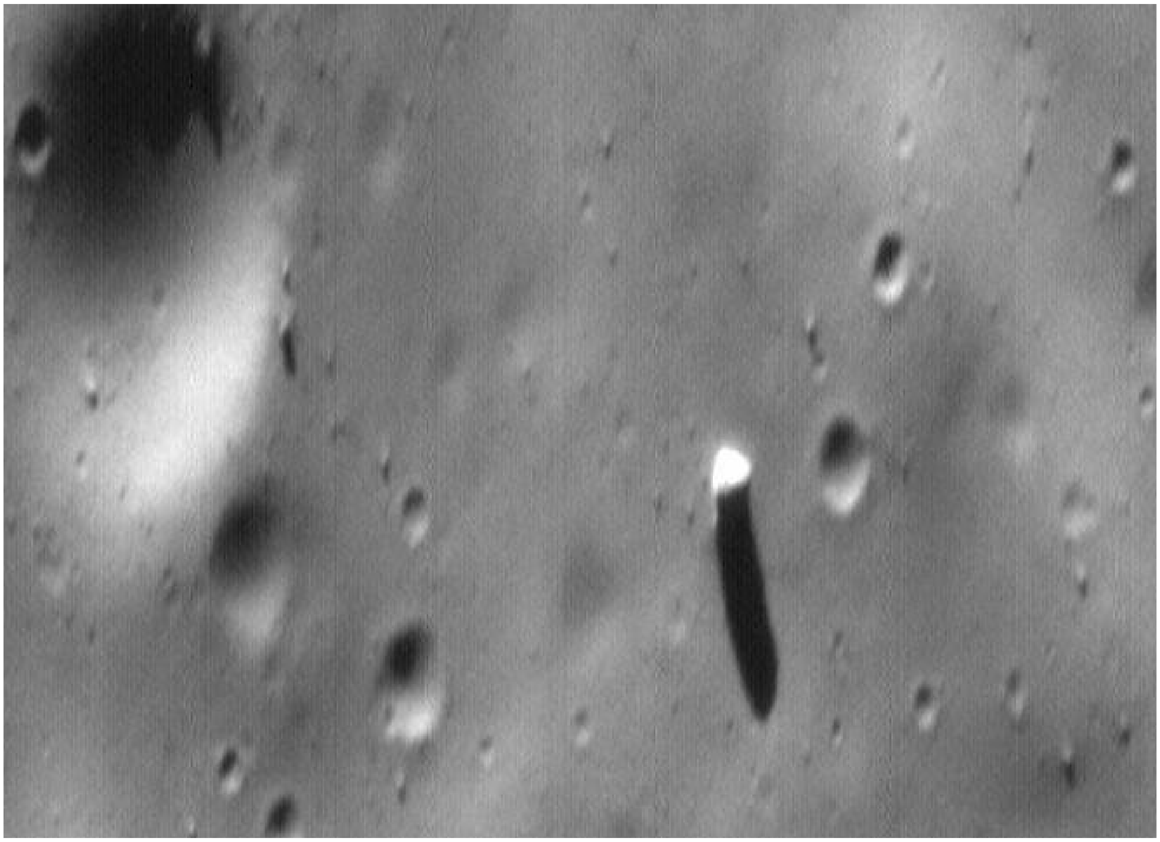
Finally, from November 1998 to March 1999, aerobraking continued and shrank the high point of the orbit down to 450 km (280 mi). At this altitude, *Surveyor* circled Mars once every two hours. Aerobraking was scheduled to terminate at the same time the orbit drifted into its proper position with respect to the Sun. In the desired orientation for mapping operations, the spacecraft always crossed the day-side equator at 14:00 (local Mars time) moving from south to north. This geometry was selected to enhance the total quality of the science return.

Mapping

The spacecraft circled Mars once every 117.65 minutes at an average altitude of 378 kilometers (235 miles). It is in a near polar orbit (inclination = 93°) which is almost perfectly circular, moving from being over the south pole to being over the north pole in just under an hour. The altitude was chosen to make the orbit sun-synchronous, so that all images that were taken by the spacecraft of the same surface features on different dates were taken under identical lighting conditions. After each orbit, the spacecraft viewed the planet 28.62° to the west because Mars had rotated underneath it. In effect, it was always 14:00 for *Mars Global Surveyor* as it moved from one time zone to the next exactly as fast as the Sun. After seven sols and 88 orbits, the spacecraft would approximately retrace its previous path, with an offset of 59 km to the east. This ensured eventual full coverage of the entire surface.

In its extended mission, MGS did much more than study the planet directly beneath it. It commonly performed rolls and pitches to acquire images off its nadir track. The roll maneuvers, called ROTOs (Roll Only Targeting Opportunities), rolled the spacecraft left or right from its ground track to shoot images as much as 30° from nadir. It was possible for a pitch maneuver to be added to compensate for the relative motion between the spacecraft and the planet. This was called a CPROTO (Compensation Pitch Roll

Targeting Opportunity), and allowed for some very high resolution imaging by the onboard MOC (Mars Orbiting Camera).



The Phobos monolith (right of center) as taken by the Mars Global Surveyor (MOC Image 55103) in 1998.

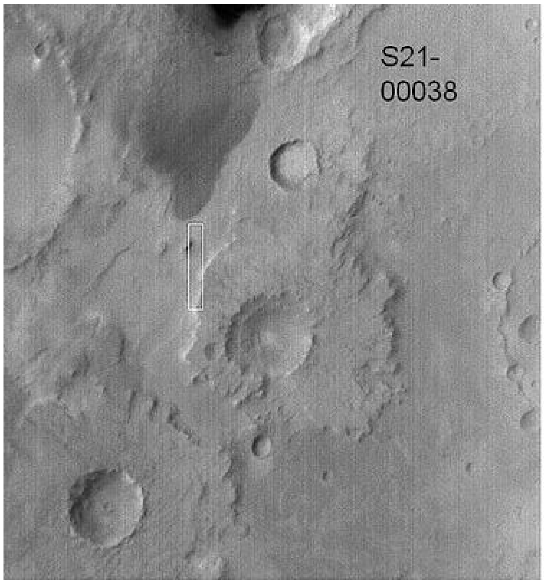
In addition to this, MGS could shoot pictures of other orbiting bodies, such as other spacecraft and the moons of Mars. In 1998 it imaged what was later called the Phobos monolith, found in MOC Image 55103.

Primary Mission Results

After analyzing hundreds of high-resolution pictures of the Martian surface taken by the orbiting Mars Surveyor spacecraft, a team of researchers found that weathering and winds on the planet create landforms, especially sand dunes, remarkably similar to those in some deserts on Earth.

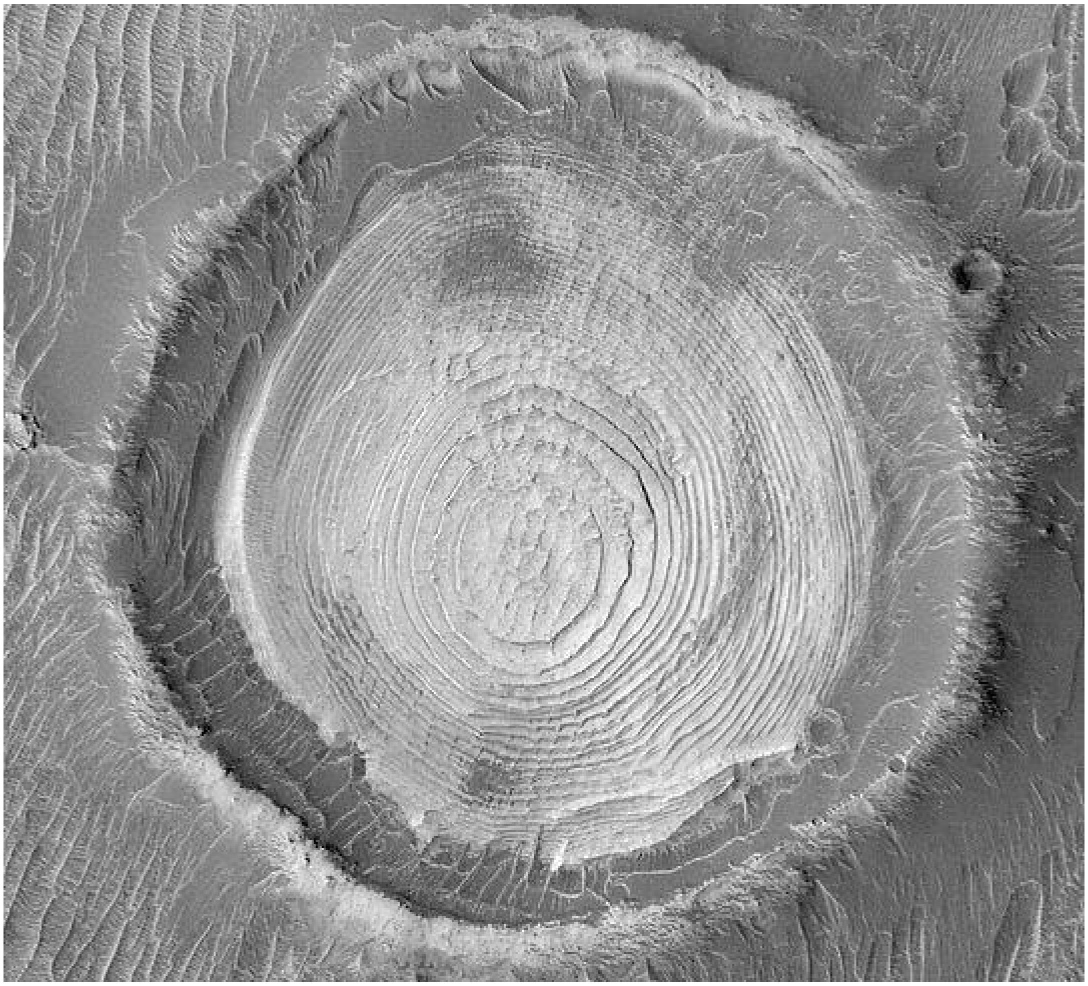
Results from the Mars Global Surveyor primary mission (1996–2001) were published in the Journal of Geophysical Research by M. Malin and K. Edgett. Some of these discoveries are:

- The planet was found to have a layered crust to depths of 10 km or more. To produce the layers, large amounts of material had to be weathered, transported and deposited.



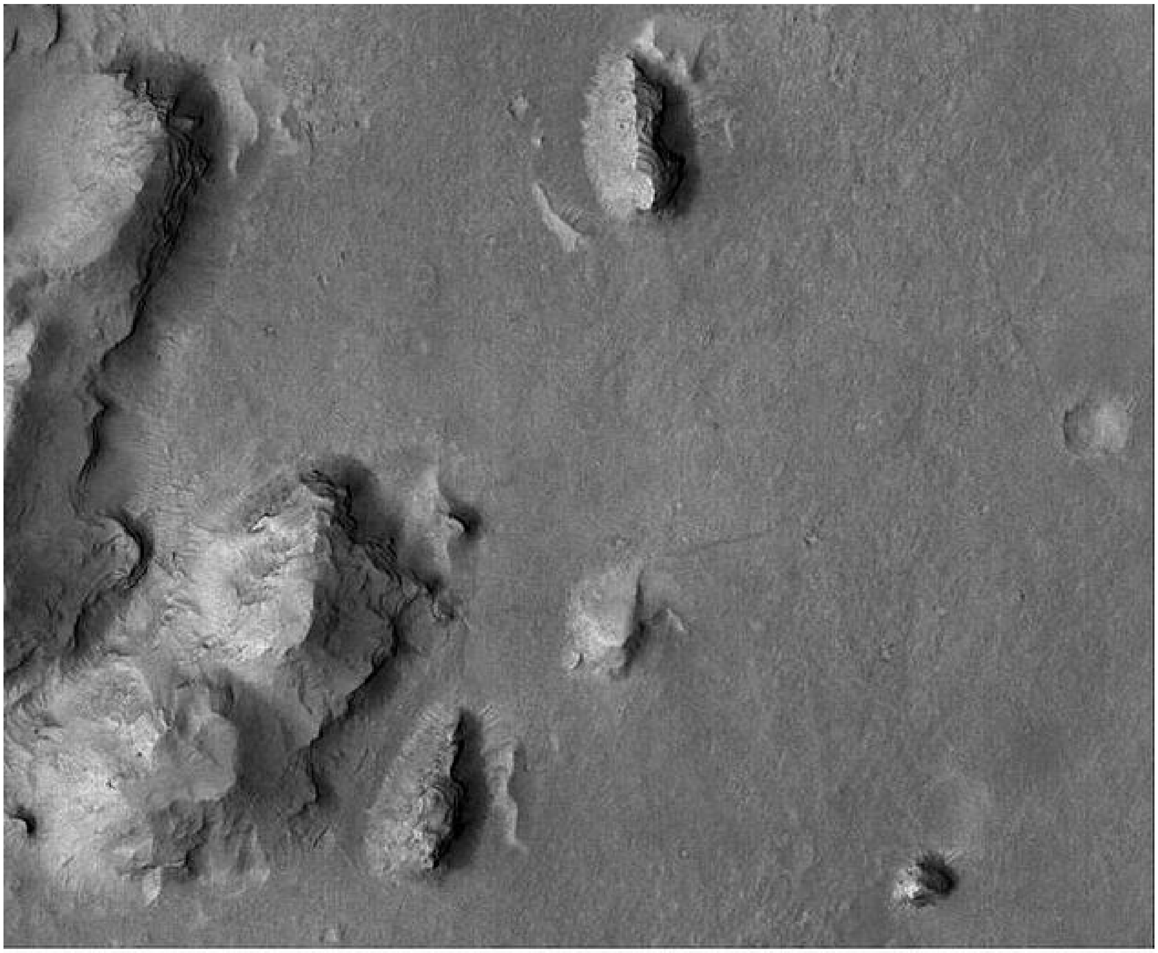
This set of images from the public target request program shows many layers on a butte near the top of the image rectangle. These craters are within the much larger crater called Tikhonravov.

Layers in an old crater in Arabia, as seen by Mars Global Surveyor (MGS). Layers may form from volcanoes, the wind, or by deposition under water. The craters on the left are pedestal craters.



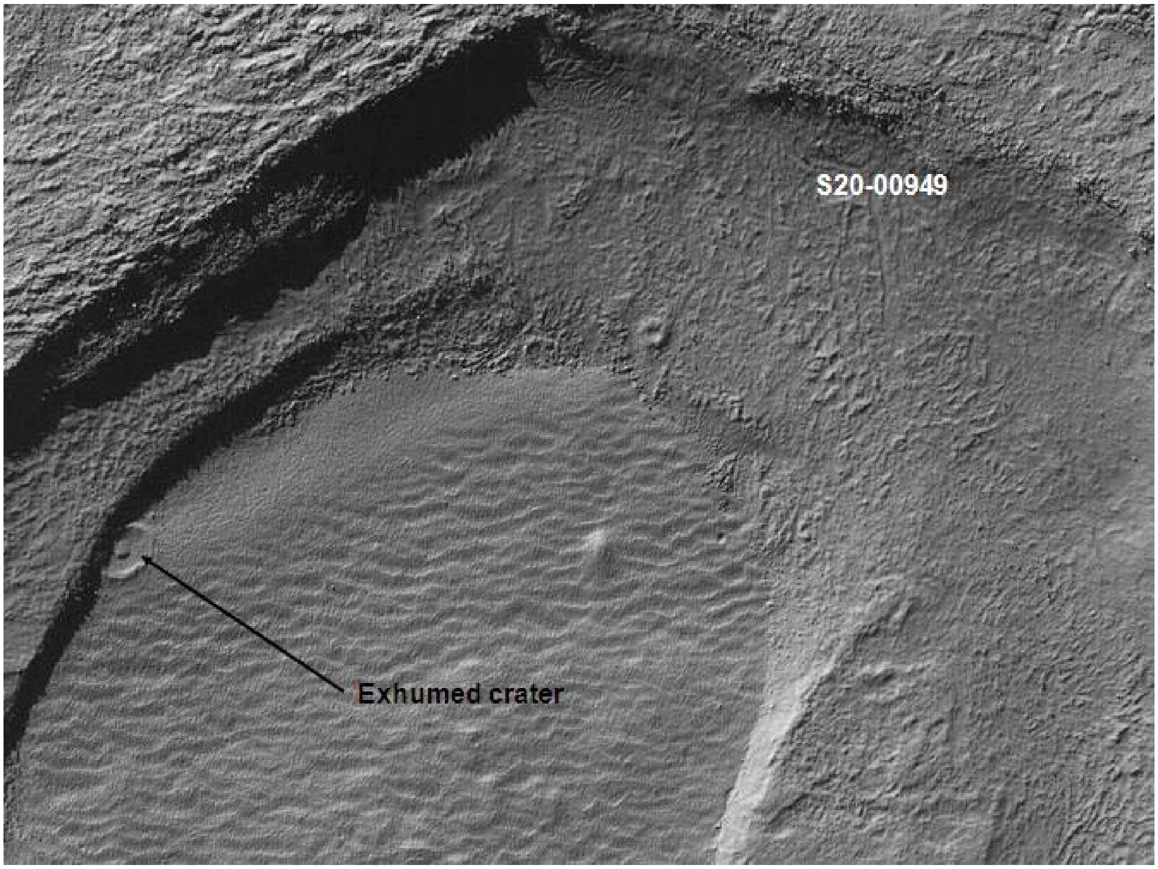
Layers in crater found within the Schiaparelli crater basin as seen by Mars Global Surveyor. Image from the Sinus Sabaeus quadrangle.

Layers in Monument Valley. These are accepted as being formed, at least in part, by water deposition. Since Mars contains similar layers, water remains as a major cause of layering on Mars.

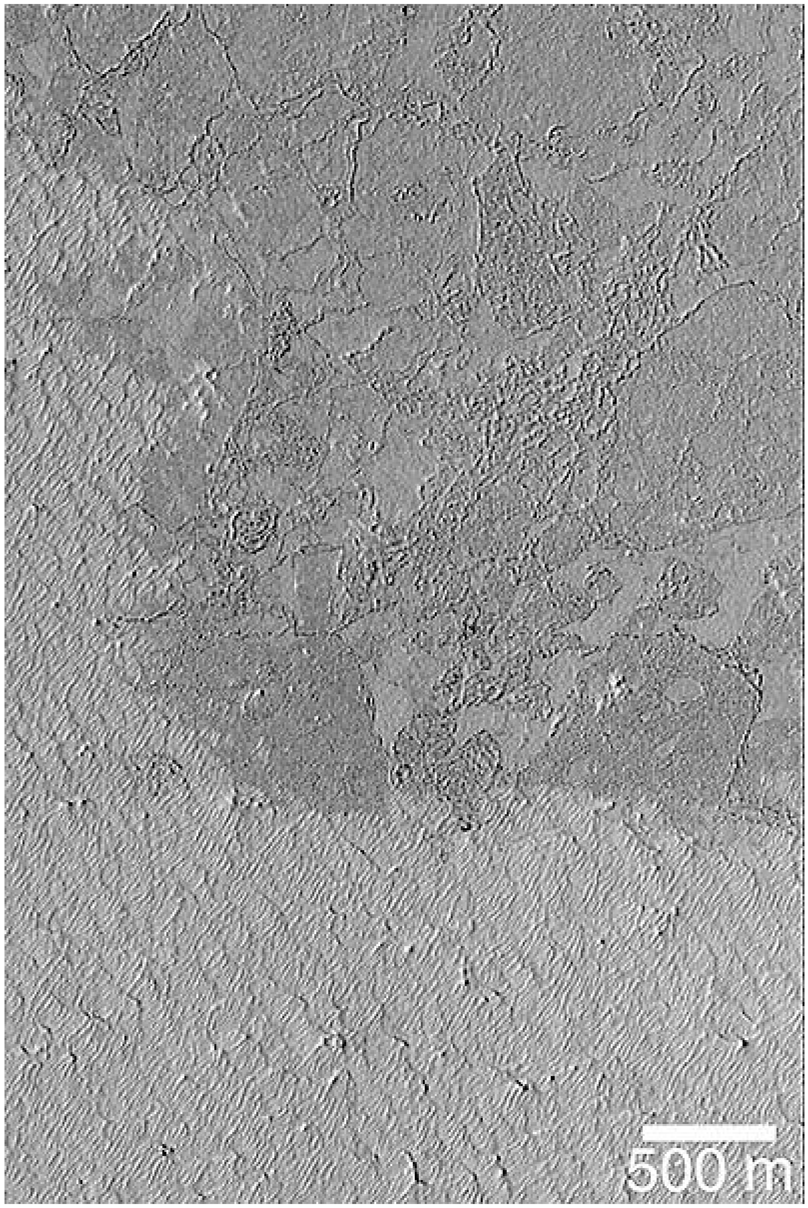


Buttes and layers in Aeolis quadrangle, as seen by Mars Global Surveyor.

- The northern hemisphere is probably just as cratered as the southern hemisphere, but the craters are mostly buried.
- Many features, like impact craters, were buried, then recently exhumed.



Crater that was buried in another age and is now being exposed by erosion, as seen by the Mars Global Surveyor. Image is located in the Noachis quadrangle.

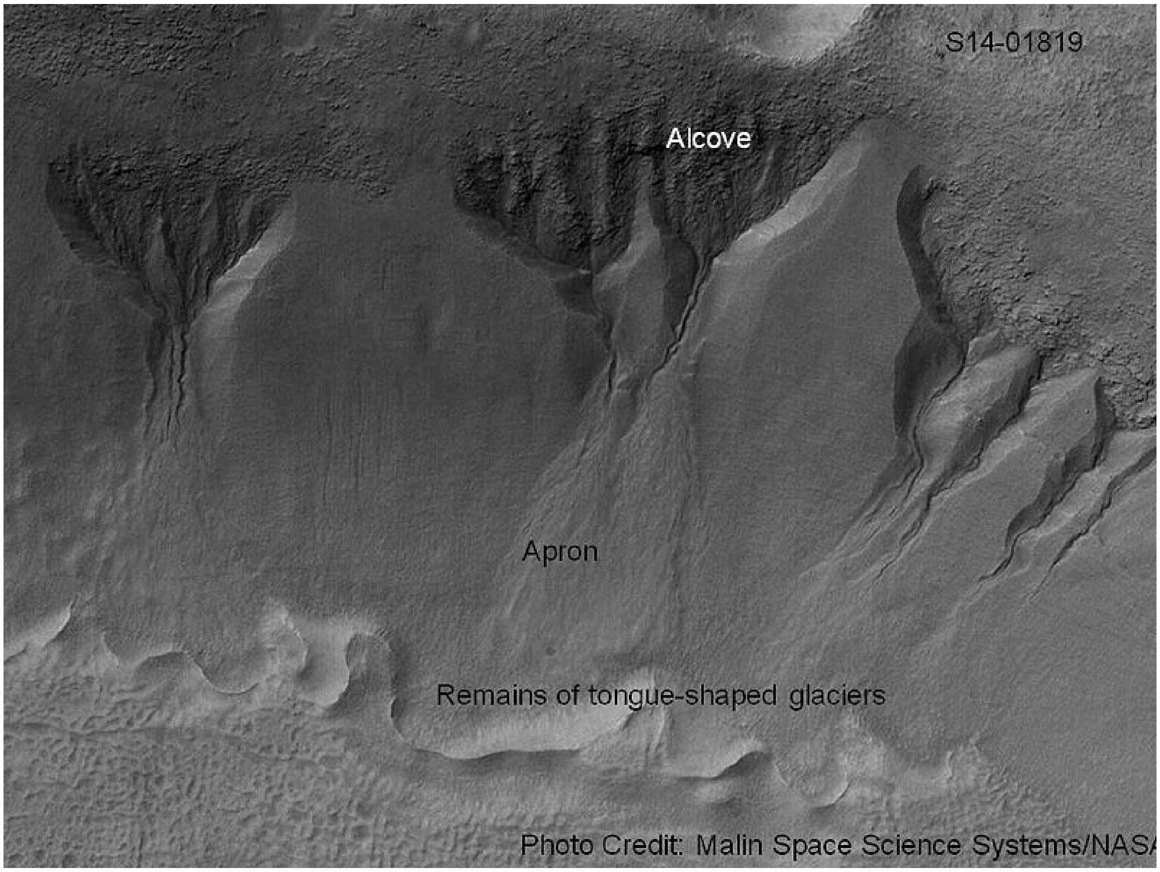


Lava flows were once covered over, now these platy flows are being exposed

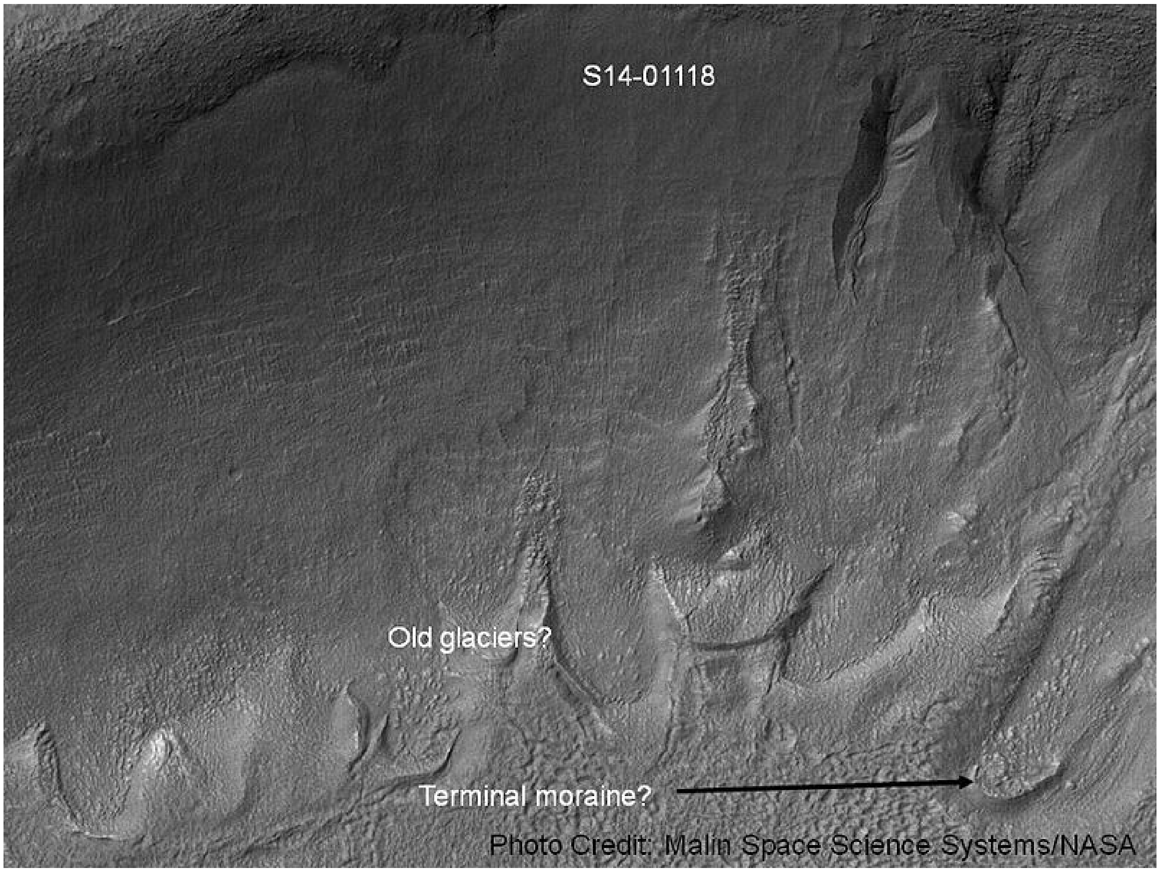
Crater was buried, now it is being exhumed by erosion. Image located in Ismenius Lacus quadrangle.

The northern hemisphere appears smooth, but the craters are covered over. Here, a group of craters are patially exposed. Image located in Cebrenia quadrangle.

- Hundreds of gullies were discovered that were formed from liquid water, possible in recent times.



Group of gullies on north wall of crater that lies west of the crater Newton (41.3047 degrees south latitude, 192.89 east longitide). Image taken with Mars Global Surveyor. Image is located in the Phaethontis quadrangle.

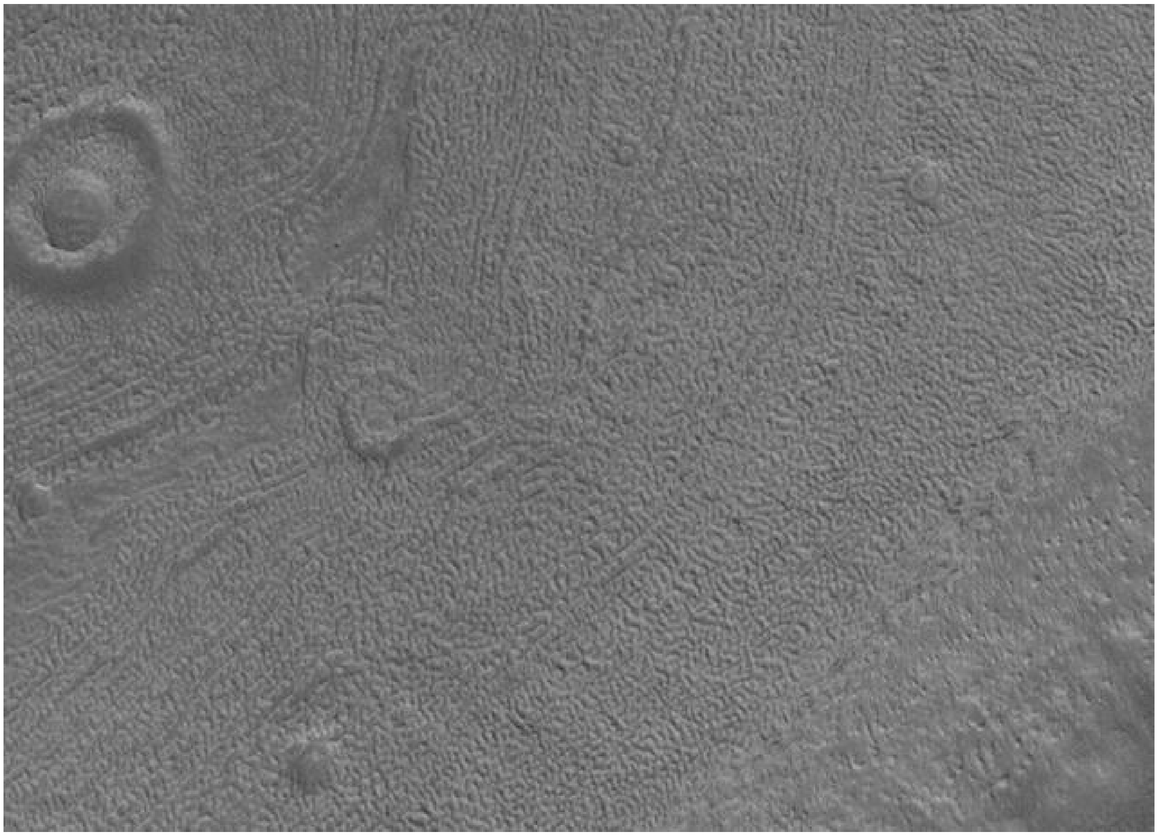


Gullies in a crater in Eridania quadrangle, north of the large crater Kepler. Also, features that may be remains of old glaciers are present. One, to the right, has the shape of a tongue.

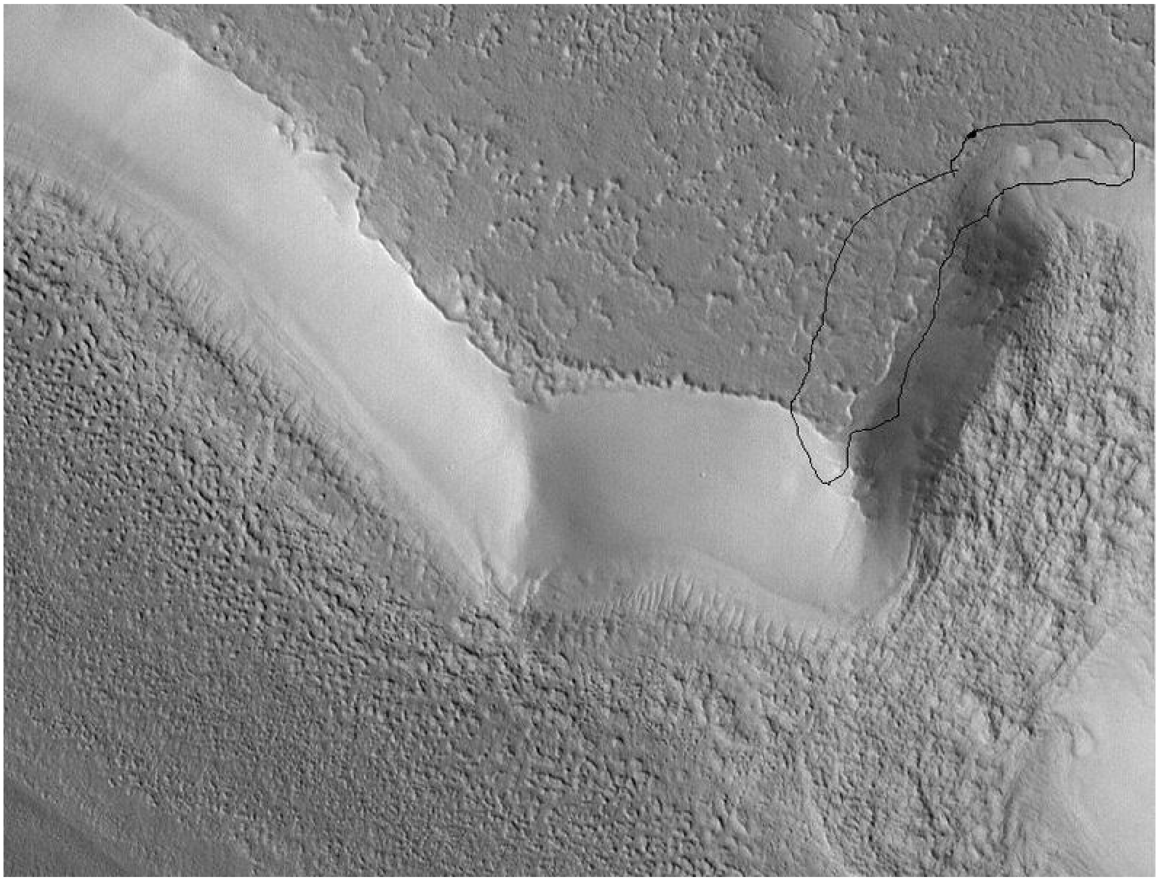
Gullies on one wall of Kaiser Crater. Gullies usually are found in only one wall of a crater.

Full color image of gullies on wall of Gorgonum Chaos. Image is located in the Phaethontis quadrangle.

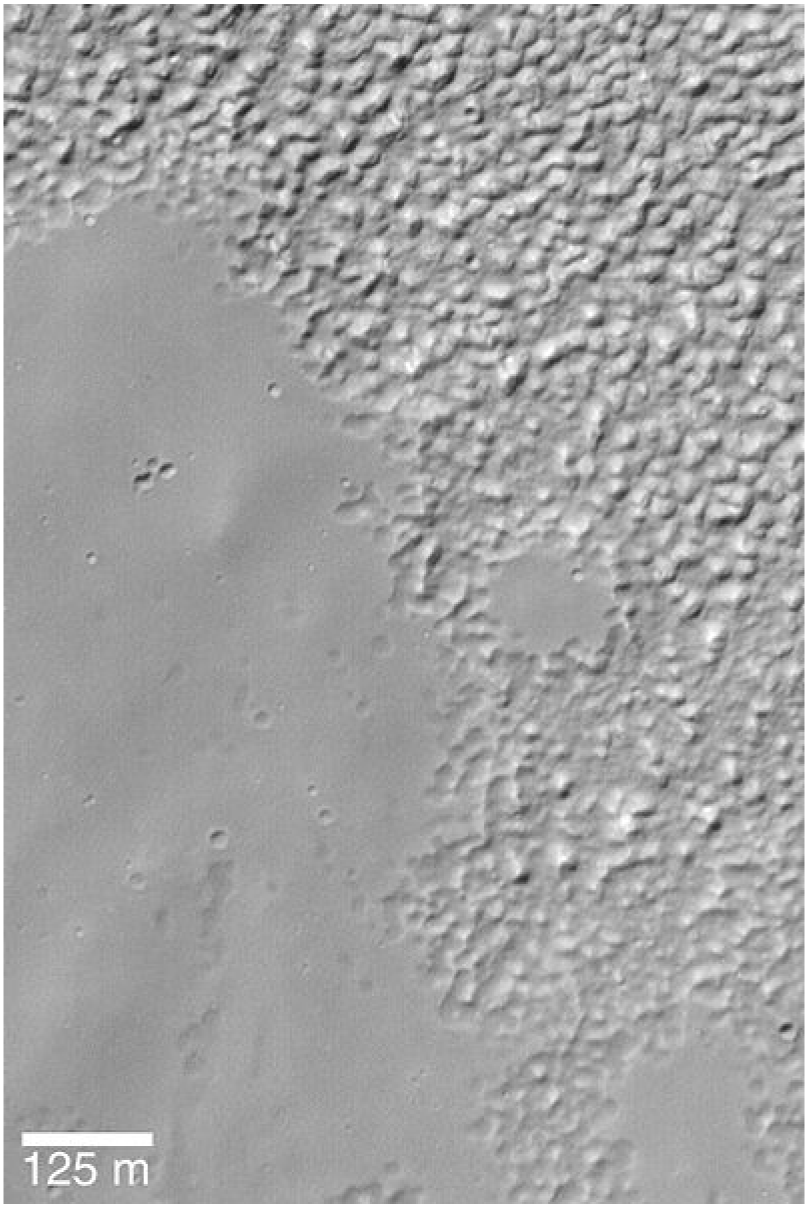
- Large areas of Mars are covered by a mantle that coats all, but the very steepest slopes. The mantle is sometimes smooth, sometimes pitted. Some believe the pits are due to the escape of water through sublimation (ice changing directly to a vapor) of buried ice.



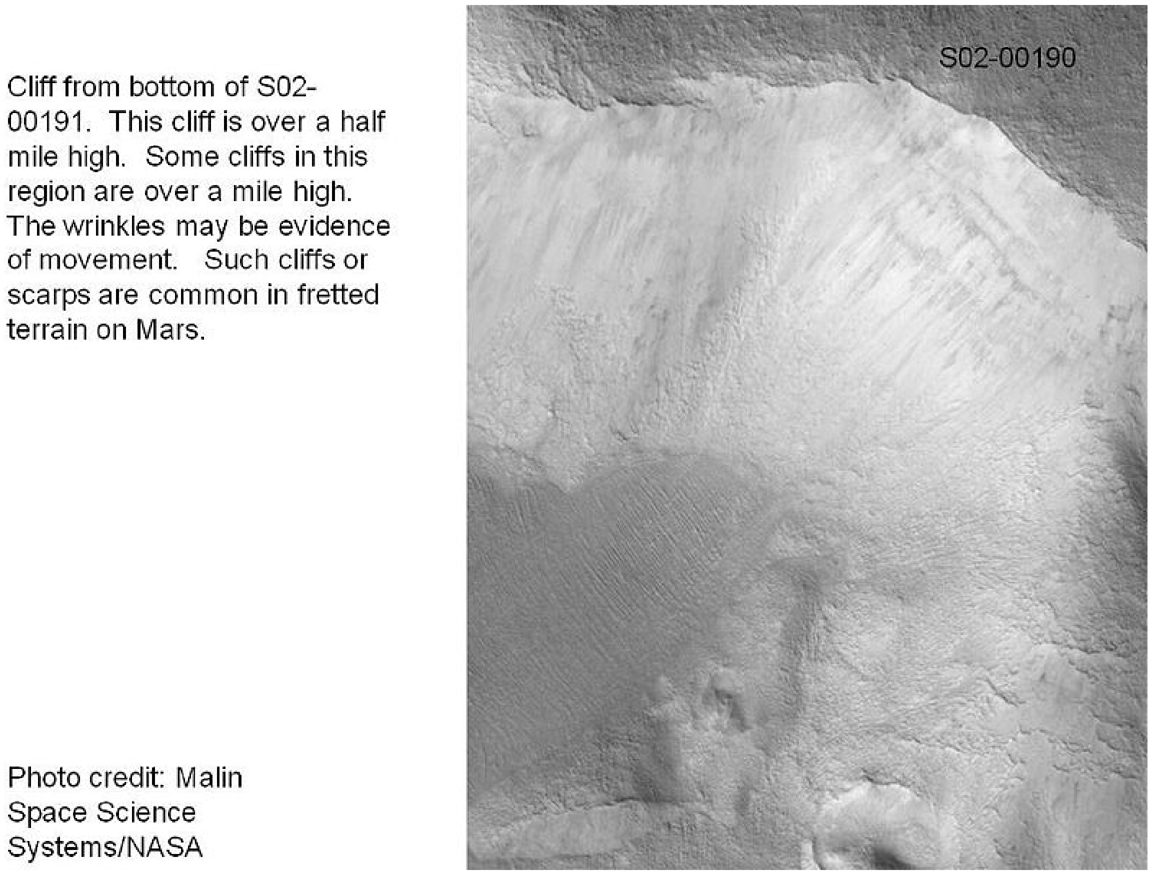
Close up image of Phaethontis surface taken with Mars Global Surveyor. Pits are thought to be caused by buried ice turning into a gas.



The mantle drapes most of the area. Note the absence of boulders on the cliff face. An area that shows the edges of the mantle is circled. Image located in Ismenius Lacus quadrangle.

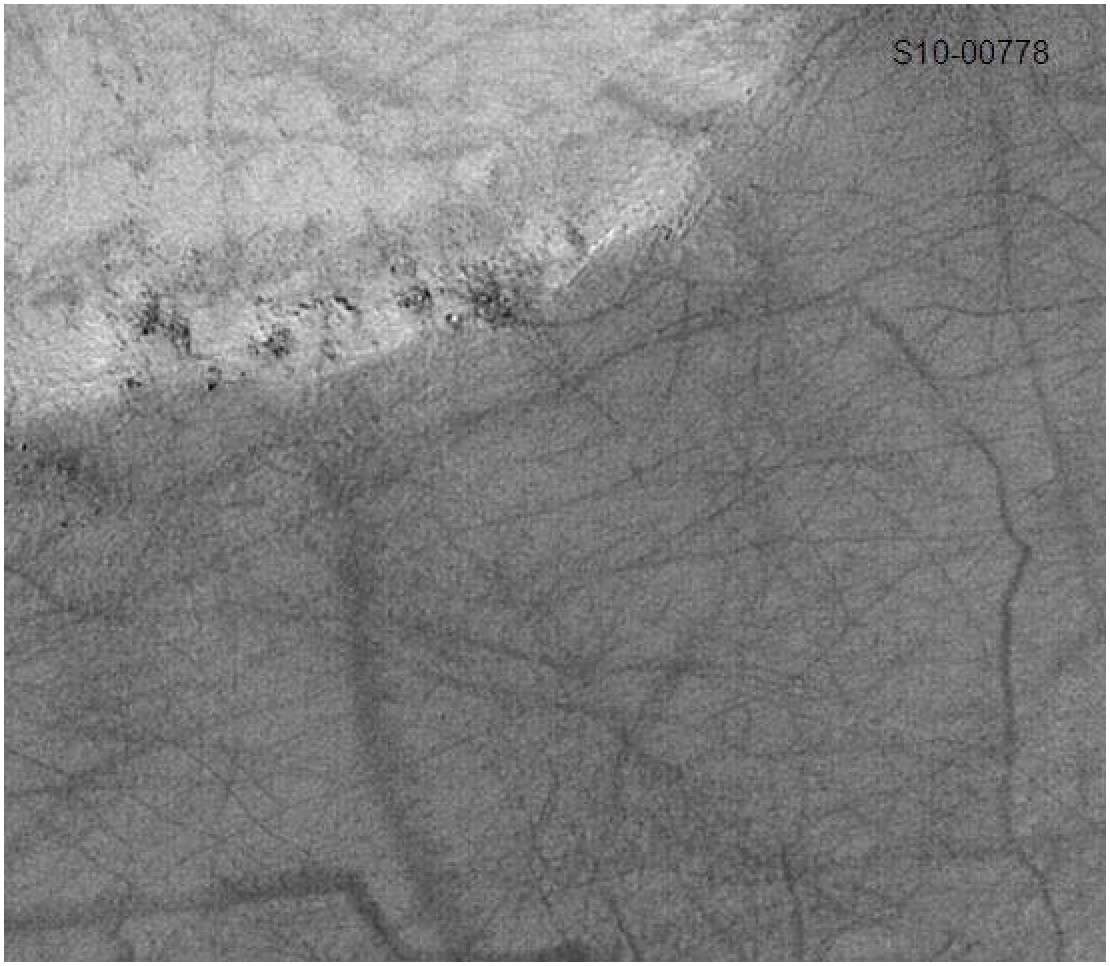


Mantle material, as seen by MGS

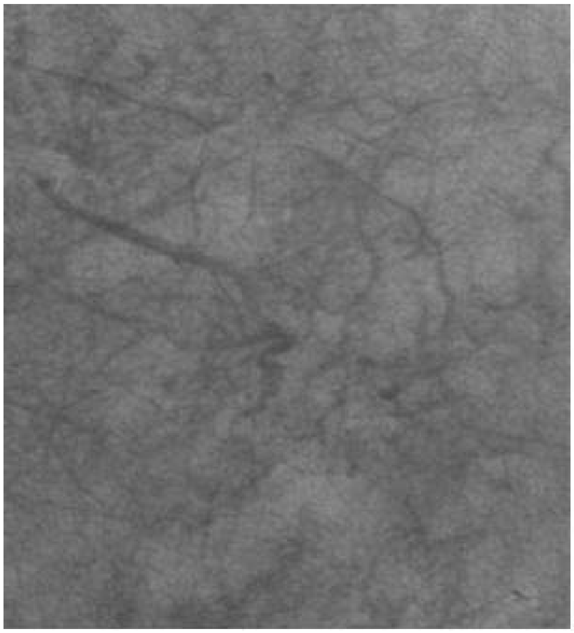


Steep Cliff in Ismenius Lacus quadrangle with smooth mantle covering its face

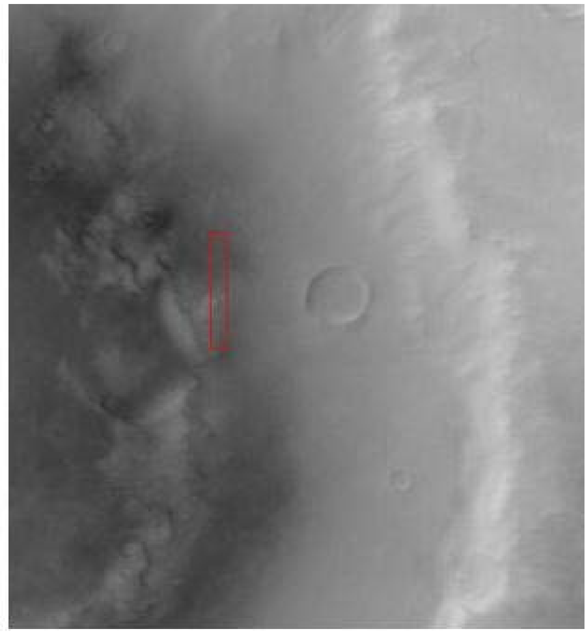
- Some areas are covered by hematite-rich material. The hematite could have been put in place by liquid water in the past.
- Dark streaks were found to be caused by giant dust devils. Dust Devil Tracks were observed to frequently change; some changed in just one month.



Pattern of large and small tracks made by giant dust devils as seen by Mars Global Surveyor. Image is located in Eridania quadrangle.

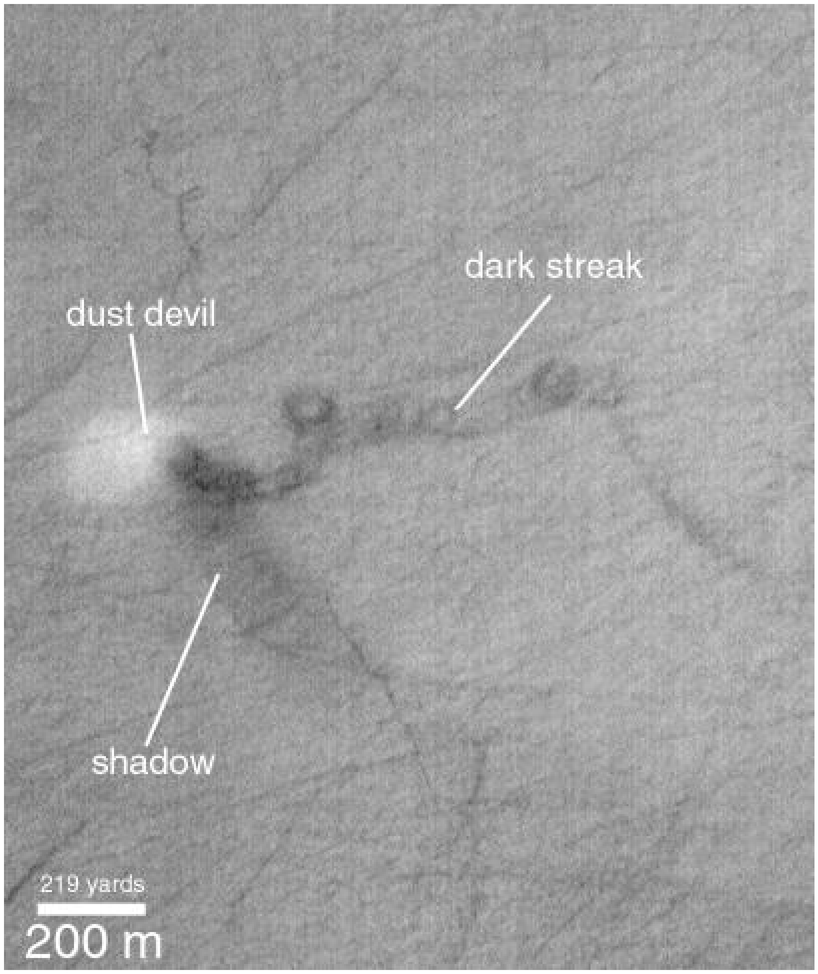


Dark curvy lines are dust devil tracks.

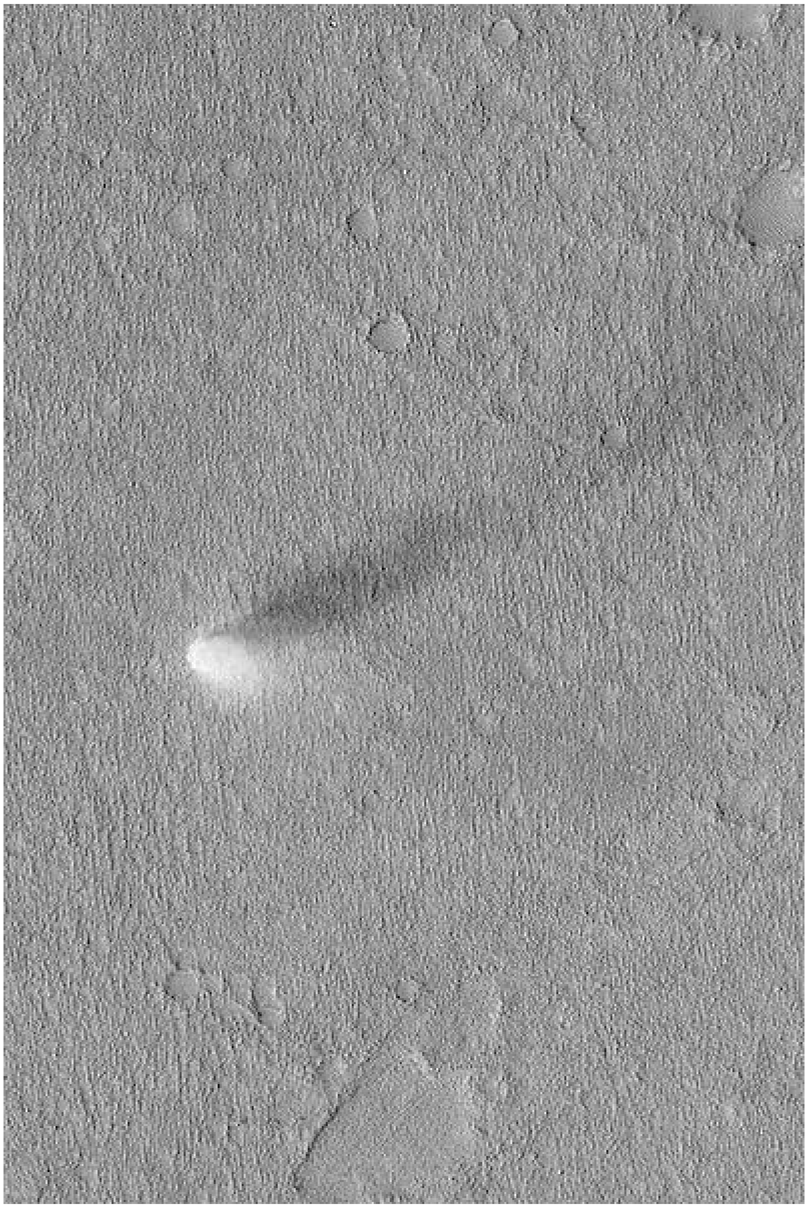


Context for image on left

Kepler (Martian crater) showing dust devil tracks, as seen by Mars Global Surveyor. Kepler is a large crater in the Eridania quadrangle.

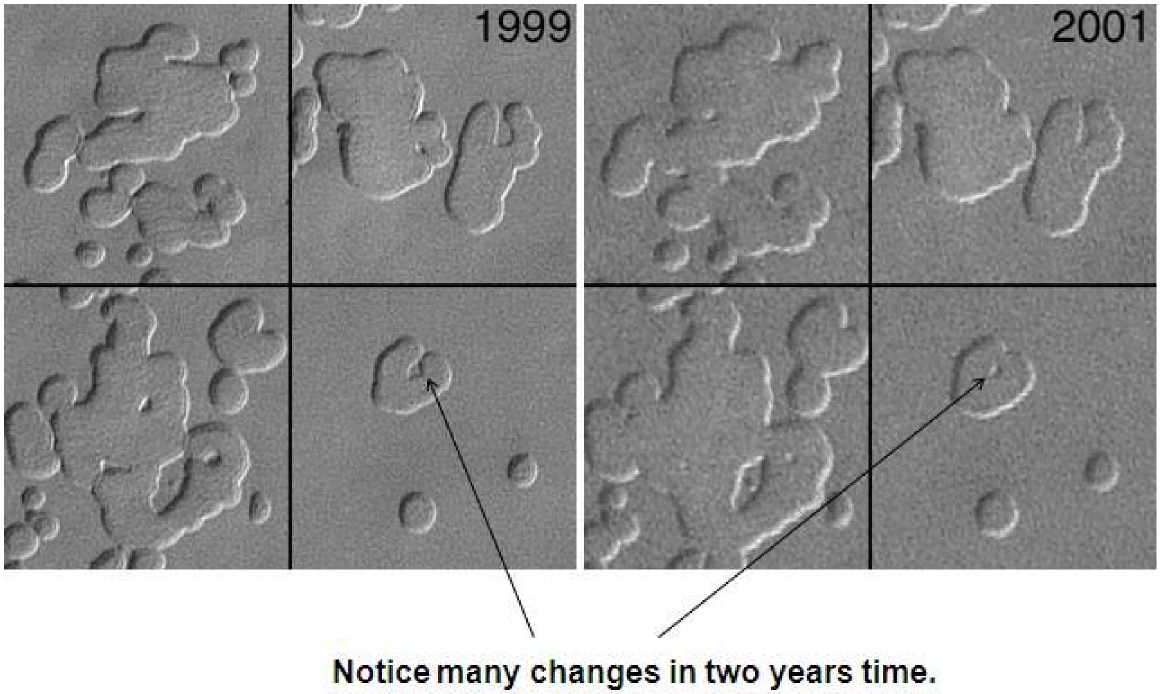


Dust Devil, as seen by MGS



Dust Devil in action showing shadow to the right. Image located in Cebrenia quadrangle.

- The south pole's residual cap was observed to look like Swiss cheese. The holes are generally a few meters deep. The holes get bigger each year, so Mars may be warming.



Changes in South Pole from 1999 to 2001, as seen by Mars Global Surveyor. Notice how swiss-cheese type holes have grown in the two years.

MER communications subsystem

Mars Global Surveyor functioned as a communications satellite relaying data back to Earth from the MER surface landers. Portions of MGS had been scheduled to remain active until at least September 2008 to support MER.

Loss of contact

On **November 2, 2006**, NASA lost contact with the spacecraft after commanding it to adjust its solar panels. Several days passed before a faint signal was received indicating that the spacecraft had entered safe mode and was awaiting further instructions.

On **November 20, 2006**, the Mars Reconnaissance Orbiter spacecraft attempted to image *Mars Global Surveyor* to verify the orientation of the orientation of the spacecraft. The effort was unsuccessful.

On **November 21 and 22, 2006**, *Mars Global Surveyor* failed to relay communications to the Opportunity rover on the surface of Mars. In response to this complication, Mars Exploration Program manager Fuk Li stated, "Realistically, we have run through the most likely possibilities for re-establishing communication, and we are facing the likelihood that the amazing flow of scientific observations from Mars Global Surveyor is over."

On **April 13, 2007,** NASA announced the loss of the spacecraft was caused by a flaw in a parameter update to the spacecraft's system software. The spacecraft was designed to hold two identical copies of the system software for redundancy and error checking. Subsequent updating to the software encountered human error when two independent operators updated separate copies with differing parameters followed by a corrective update that unknowingly included a memory fault which resulted in the loss of the spacecraft.

Previously, in November of 2005, two operators had changed unknowingly, the same parameter on separate copies of the system software. Each operator had used a slightly different precision when inputting a parameter, which resulted in a small but significant difference in the two copies. A subsequent memory readout revealed this inconsistency to the mission's team.

In order to correct the error, an update was drafted in June of 2006. However, two memory addresses were incorrectly handled in the update, which could allow values to be written into the wrong memory addresses and further complications with the mission. Five months later, the problematic memory addresses were called, resulting in the solar arrays being driven until they hit a hard stop and became unmovable. The complication lead the spacecraft to incorrectly diagnose a failure of a gimbal motor causing the spacecraft to rotate to allow the unmovable solar array to point toward the Sun. However, in this position the remaining usable battery was also directed toward the Sun, resulting in the battery overheating and eventually failing. The spacecraft subsequently went into safe mode and contact with the spacecraft was lost.

Originally, the spacecraft was intended to observe Mars for 1 Martian year (approximately 2 Earth years). However, based on the vast amount of valuable science data returned, NASA had previously extended the mission three times.

MGS and general relativity: the Lense-Thirring test

Data from MGS have also been used to perform a test of the general relativistic Lense-Thirring effect which consists of a small precession of the orbital plane of a test particle moving around a central, rotating mass such as a planet. The interpretation of the out-of-plane Root-Mean-Square (RMS) time series of MGS in terms of such a relativistic feature of motion by L. Iorio was criticized by K. Krogh; however, L. Iorio supported his thesis with new arguments.

Discovery of water on Mars

Inner channel on floor of Nanedi Valles that suggests that water flowed for a fairly long period. Image from Lunae Palus quadrangle.

On 6 December 2006 NASA released photos of two craters called Terra Sirenum and Centauri Montes which appear to show the presence of water on Mars at some point between 1999 and 2001. The pictures were produced by the Mars Global Surveyor and are quite possibly the spacecraft's final contribution to our knowledge of Mars and the question of whether life or water exists on the planet.

Hundreds of gullies were discovered that were formed from liquid water, possible in recent times. These gullies occur on steep slopes and mostly in certain bands of latitude.

A few channels on Mars displayed inner channels that suggest sustained fluid flows. The most well-known is the one in Nanedi Valles. Another was found in Nirgal Vallis.

Mission timeline

- 7 November 1996: Launch from Cape Canaveral.
- 11 September 1997: Arrival at Mars, began orbit insertion.
- 1 April 1999: Primary mapping phase began.
- 1 February 2001: First extended mission phase began.
- 1 February 2002: Second extended mission phase began.
- 1 January 2003: Relay mission began.
- 30 March 2004: *Surveyor* photographed the Mars Exploration Rover *Spirit* along with its wheel tracks showing its first 85 sols of travel.
- 1 December 2004: Science and Support mission began.
- April 2005: MGS became the first spacecraft to photograph another spacecraft in orbit around a planet other than Earth when it captured two images of the Mars Odyssey spacecraft and one image of the Mars Express spacecraft.
- 1 October 2006: Extended mission phase began for another two years.
- 2 November 2006: Spacecraft suffers an error while attempting to reorient a solar panel and communication was lost.
- 5 November 2006: Weak signals were detected, indicating the spacecraft was awaiting instructions. The signal cut out later that day.
- 21 November 2006: NASA announces the spacecraft has likely finished its operating career.
- 6 December 2006: NASA releases imagery taken by MGS of a newly found gully deposit, suggesting that water still flows on Mars.
- 13 April 2007: NASA releases its Preliminary Report on the cause(s) of MGS' loss of contact.

Chapter- 6

Space and Solar System Exploration in 1997

Advanced Composition Explorer

Advanced Composition Explorer (ACE)

An artist's concept of ACE

Operator	NASA
Mission type	Orbiter
Satellite of	Earth
Launch date	August 25, 1997
Launch vehicle	Delta II
Mission duration	8-25-1997 to 2024
COSPAR ID	1997-045A
Homepage	Advanced Composition Explorer Home
Mass	596 kilograms (1,313 lb)
Power	44 Watts
	Orbital elements
Semimajor axis	2.57
Eccentricity	0.98967
Inclination	28.7°
Apoapsis	1,256,768 kilometers (780,919 mi)
Periapsis	179 kilometers (111 mi)
Orbital period	1,398 hours (58.25 days)

Advanced Composition Explorer (ACE) is a NASA space exploration mission being conducted as part of the Explorer program to study matter *in situ*, comprising energetic particles from the solar wind, the interplanetary medium, and other sources. Real-time data from ACE is used by the Space Weather Prediction Center to improve forecasts and warnings of solar storms. The ACE robotic spacecraft was launched August 25, 1997 and is currently operating in a Lissajous orbit close to the L1 Lagrange point (which lies between the Sun and the Earth at a distance of some 1.5 million km from the latter). The spacecraft is still in generally good condition, and has enough fuel to maintain its orbit until 2024. NASA Goddard Space Flight Center managed the development and integration of the ACE spacecraft.

Instrumentation

Cosmic Ray Isotope Spectrometer (CRIS): CRIS determines the isotope composition of galactic cosmic rays. It is designed to be sensitive enough to detect isotopes up to the range of zinc (Z-30).

ACE Real Time Solar Wind (RTSW):

Solar Wind Ion Mass Spectrometer (SWIMS) and Solar Wind Ion Composition Spectrometer (SWICS): These two instruments are time-of-flight mass spectrometers, each tuned for a different set of measurements. They analyze the chemical and isotopic composition of solar wind and interstellar matter.

Ultra-Low Energy Isotope Spectrometer (ULEIS): ULEIS measures ion flux and is sensitive to a range from helium through nickel to determine the makeup of solar energetic particles and the mechanism by which the particles become charged by the sun.

Solar Energetic Particle Ionic Charge Analyzer (SEPICA): As of 2008, this instrument is no longer functioning due to failed gas valves.

Solar Isotope Spectrometer (SIS):

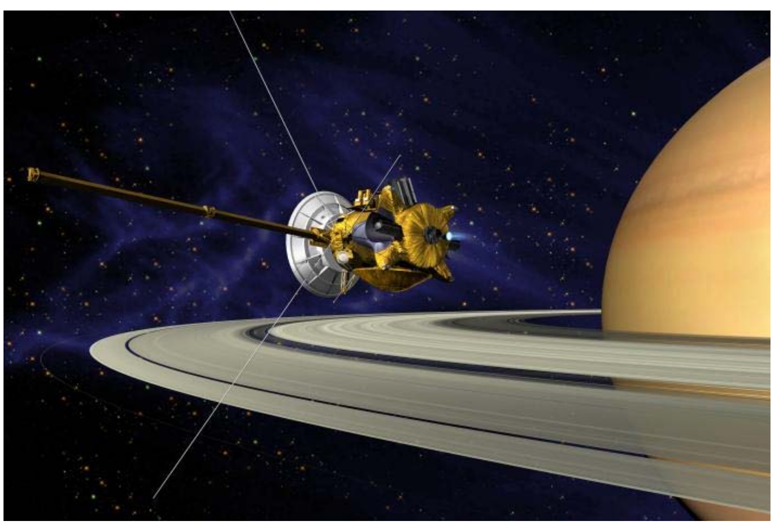
Solar Wind Electron, Proton and Alpha Monitor (SWEPAM):

Electron, Proton, and Alpha-particle Monitor (EPAM):

Magnetometer (MAG):

Cassini–Huygens

Cassini–Huygens



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

Operator	NASA / ESA / ASI
Mission type	Flyby, orbiter, lander
Flyby of	Venus, Moon, Earth, Masursky, Jupiter, Saturn's moons
Satellite of	Saturn
Orbital insertion date	2004-07-01 02:48:00 UTC
Launch date	1997-10-15 08:43:00 UTC (13 years, 3 months, and 1 day ago)
Launch vehicle	Titan IV-B / Centaur
Launch site	Space Launch Complex 40 Cape Canaveral Air Force Station
Mission duration	In Progress (Solstice) (6 years, 6 months, and 15 days elapsed) Venus 1st flyby *(completed 1998-04-26)* Venus 2nd flyby *(completed 1999-06-24)* Moon flyby *(completed 1999-08-18)* Earth flyby *(completed 1999-08-18)* Masursky flyby *(completed 2000-01-23)* Jupiter flyby *(completed 2000-12-30)* Huygens probe *(completed 2005-01-14)* Primary mission *(completed 2008-06-3-30)* Equinox mission *(completed 2010-09-27)*
COSPAR ID	1997-061A

Homepage	saturn.jpl.nasa.gov
Mass	2,523 kg (5,560 lb)
Power	640 W (3 RTGs)

Cassini–Huygens is a joint NASA/ESA/ASI robotic spacecraft mission currently studying the planet Saturn and its many natural satellites. The spacecraft consists of two main elements: the NASA-designed and -constructed *Cassini* orbiter, named for the Italian-French astronomer Giovanni Domenico Cassini, and the ESA-developed *Huygens* probe, named for the Dutch astronomer, mathematician and physicist Christiaan Huygens. The complete *Cassini* space probe was launched on October 15, 1997, and after a long interplanetary voyage, it entered into orbit around Saturn on July 1, 2004. On December 25, 2004, the *Huygens* probe was separated from the orbiter at approximately 02:00 UTC. Then, it reached Saturn's moon Titan on January 14, 2005, when it made a descent into Titan's atmosphere, and downwards to the surface, radioing scientific information back to the Earth by telemetry. This was the first landing ever accomplished in the outer solar system. On April 18, 2008, NASA announced a two-year extension of the funding for ground operations of this mission, at which point it was renamed to **Cassini Equinox Mission**. This was again extended in February 2010 with the mission now continuing until 2017. *Cassini* is the fourth space probe to visit Saturn and the first to enter orbit.

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

Objectives

Cassini has seven primary objectives:

1. Determine the three-dimensional structure and dynamic behavior of the rings of Saturn
2. Determine the composition of the satellite surfaces and the geological history of each object
3. Determine the nature and origin of the dark material on Iapetus's leading hemisphere
4. Measure the three-dimensional structure and dynamic behavior of the magnetosphere

5. Study the dynamic behavior of Saturn's atmosphere at cloud level
6. Study the time variability of Titan's clouds and hazes
7. Characterize Titan's surface on a regional scale

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

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

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

History

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

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

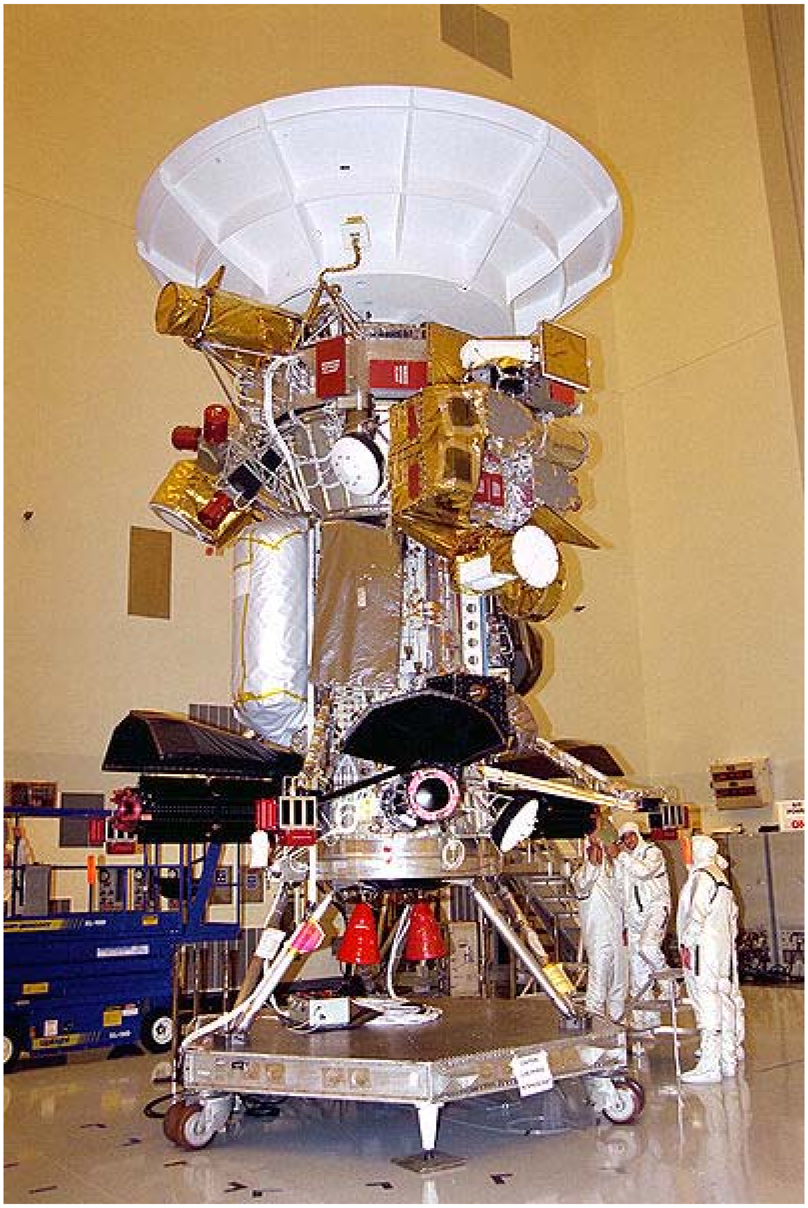
American astronaut Sally Ride, in her influential 1987 report "NASA Leadership and America's Future in Space", also examined and approved of the *Cassini* mission.

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

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

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

Spacecraft design



Cassini assembly

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

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

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

Instruments

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

Cassini Plasma Spectrometer (CAPS)

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

Cosmic Dust Analyzer (CDA)

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

Composite Infrared Spectrometer (CIRS)

The CIRS is a remote sensing instrument that measures the infrared waves coming from objects to learn about their temperatures, thermal properties, and compositions. Throughout the Cassini–Huygens mission, the CIRS will measure infrared emissions from atmospheres, rings and surfaces in the vast Saturn system. It will map the atmosphere of Saturn in three dimensions to determine temperature and pressure profiles with altitude, gas composition, and the distribution of aerosols and clouds. It will also measure thermal characteristics and the composition of satellite surfaces and rings.

Ion and Neutral Mass Spectrometer (INMS)

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

Imaging Science Subsystem (ISS)

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

Dual Technique Magnetometer (MAG)

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

Magnetospheric Imaging Instrument (MIMI)

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

Radar

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

Radio and Plasma Wave Science instrument (RPWS)

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

Radio Science Subsystem (RSS)

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

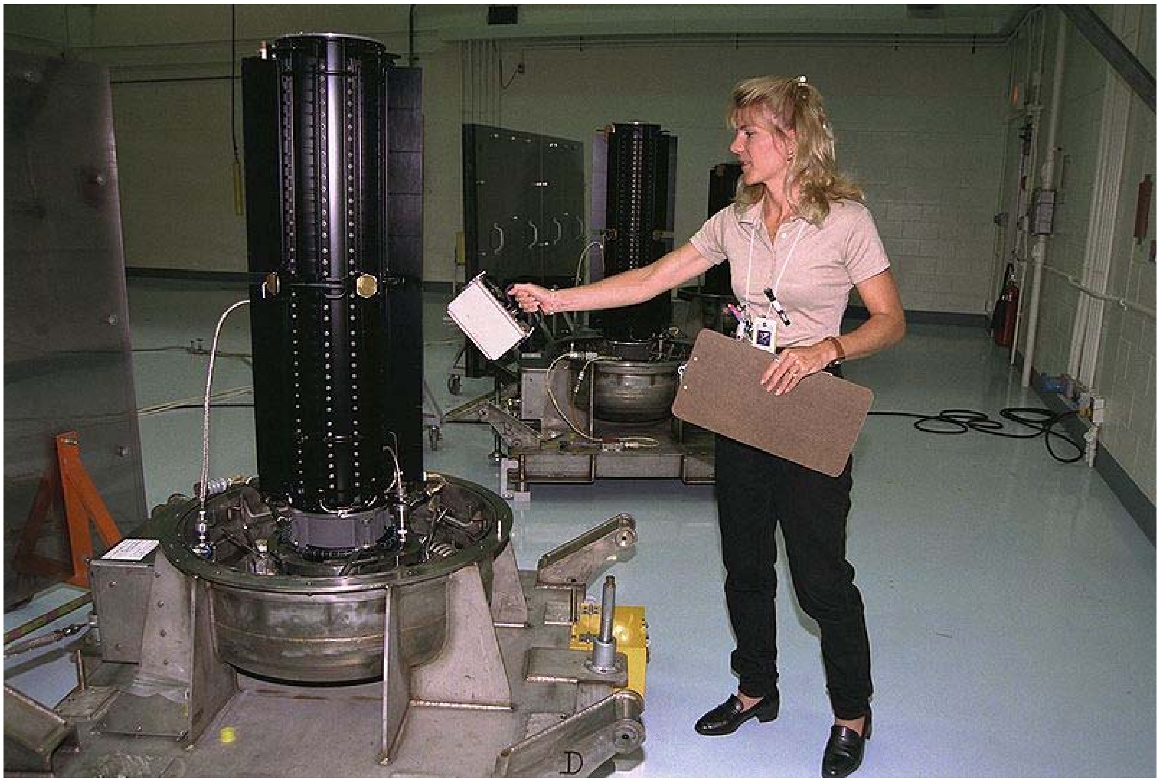
Ultraviolet Imaging Spectrograph (UVIS)

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

Visible and Infrared Mapping Spectrometer (VIMS)

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

Plutonium power source



Inspection of *Cassini* spacecraft RTGs before launch

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

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

Huygens *probe*

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

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

Important events and discoveries

Venus and Earth fly-bys and the cruise to Jupiter

Picture of the Moon during flyby

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

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

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

Jupiter flyby

Jupiter flyby picture

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

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

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

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

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

Tests of Einstein's Theory of General Relativity

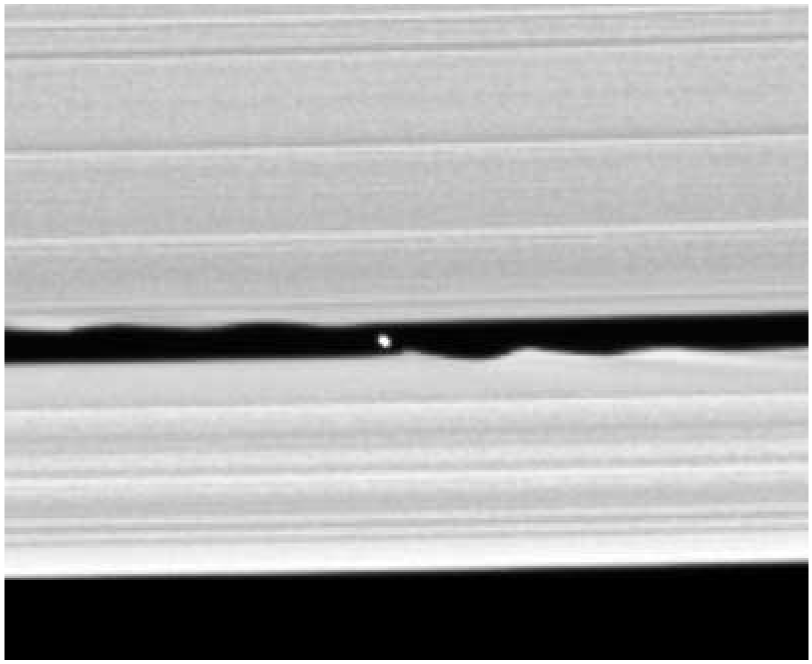
On October 10, 2003, the *Cassini* science team announced the results of tests of Einstein's Theory of General Relativity, which were done by using radio waves that were transmitted from the *Cassini* space probe.

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

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

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

New moons of Saturn



Discovery photograph of moon Daphnis

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

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

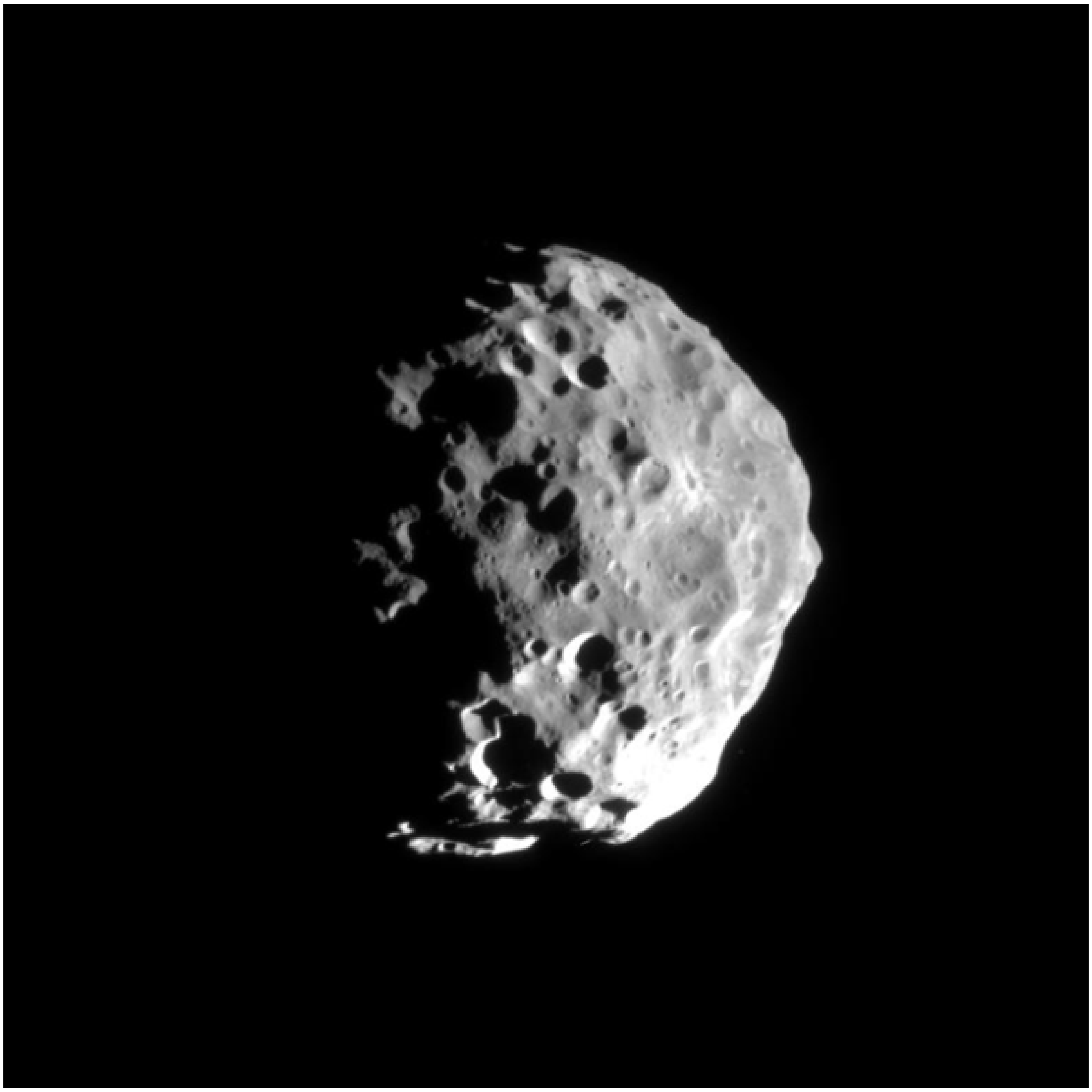


Image of Phoebe

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

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

Phoebe flyby

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

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

Saturn rotation

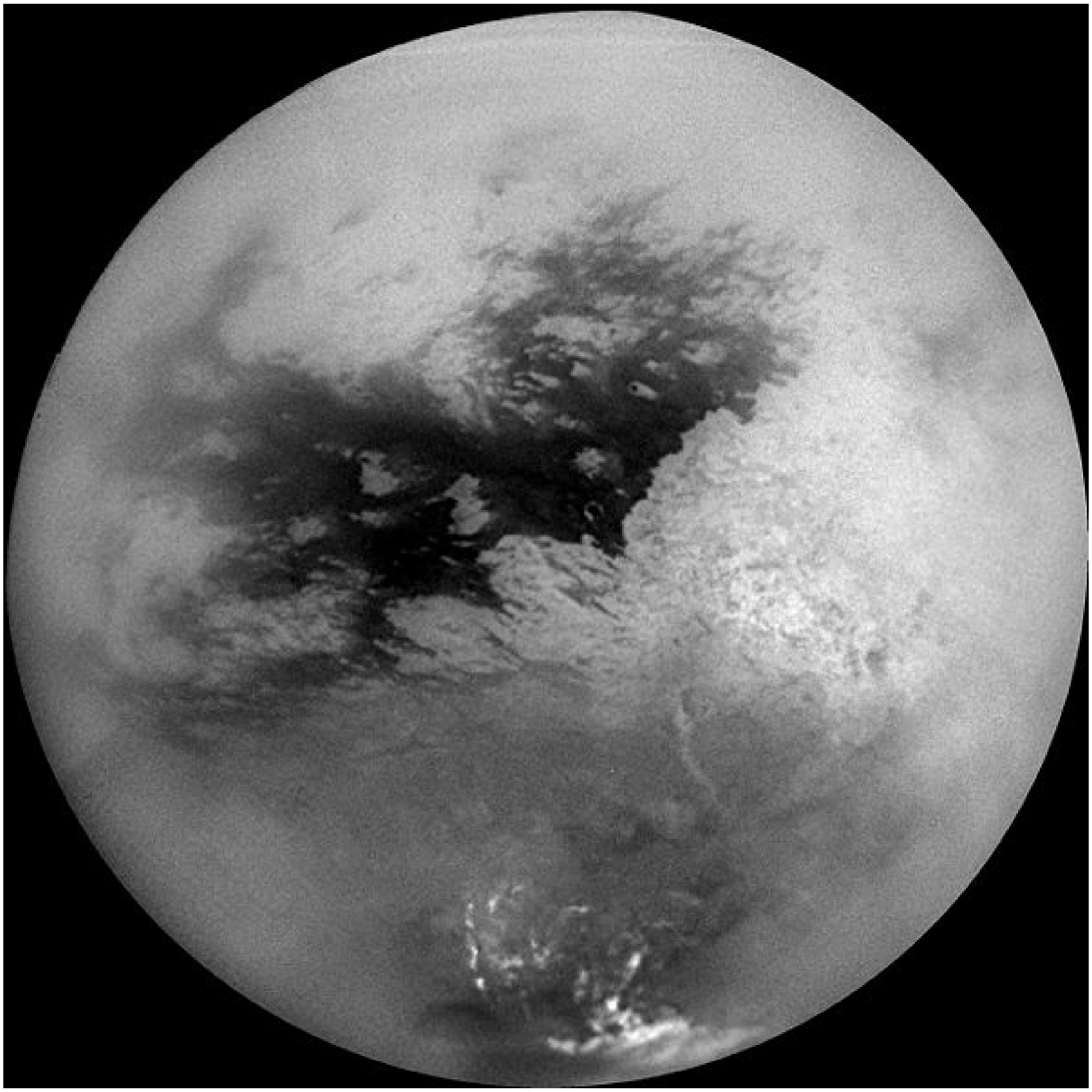
In an announcement on June 28, 2004, *Cassini* program scientists described the measurement of the rotational period of Saturn. Since there are no fixed features on the surface that can be used to obtain this period, the repetition of radio emissions was used. These new data agree with the latest values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

Orbiting Saturn

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

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

Titan flybys

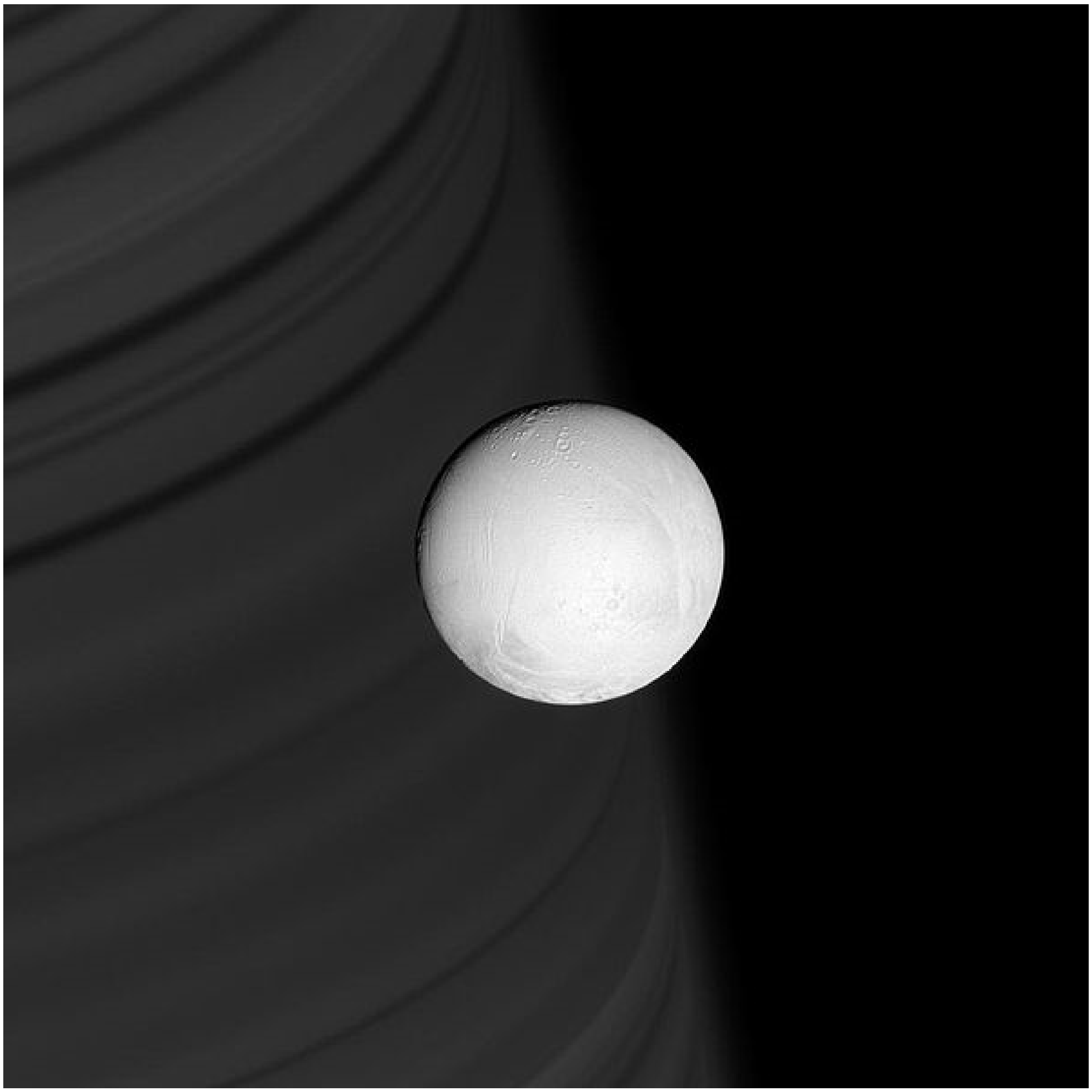


Titan's surface

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

Images with up to 100 times better "resolution" were taken and are typical of resolutions planned for subsequent Titan flybys. (Note that "resolution" refers to the clarity and precision of pictures, and that it has nothing to do with the overall size of the pictures in square centimeters, as is very commonly erroneously stated.)

Huygens' encounter with Titan



Enceladus backdropped by Saturn's ring shadows

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

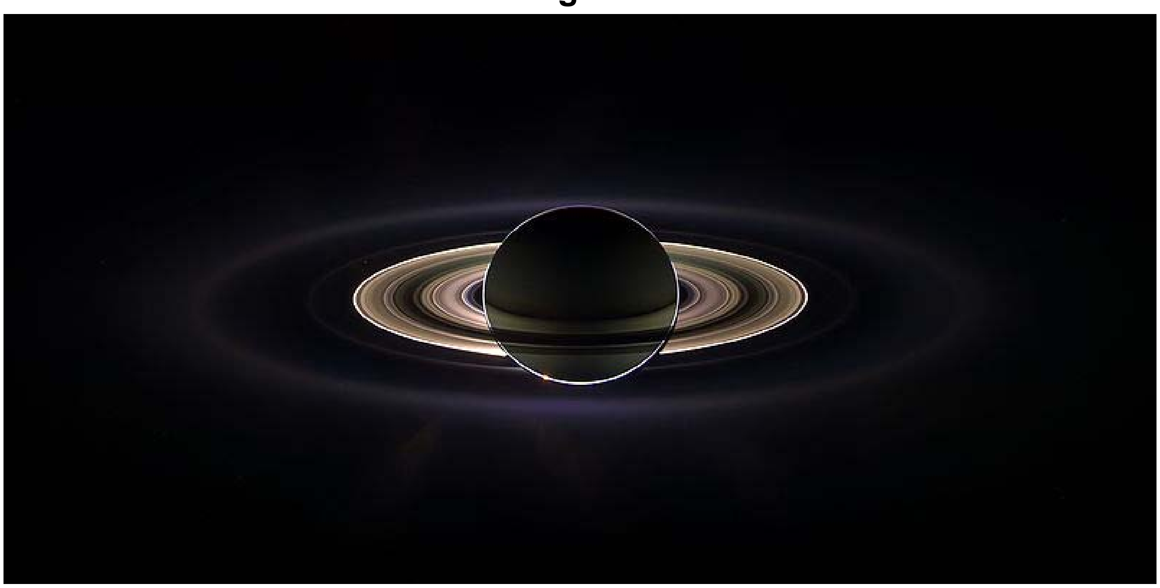
Enceladus flybys

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

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

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

Radio occultations of Saturn's rings



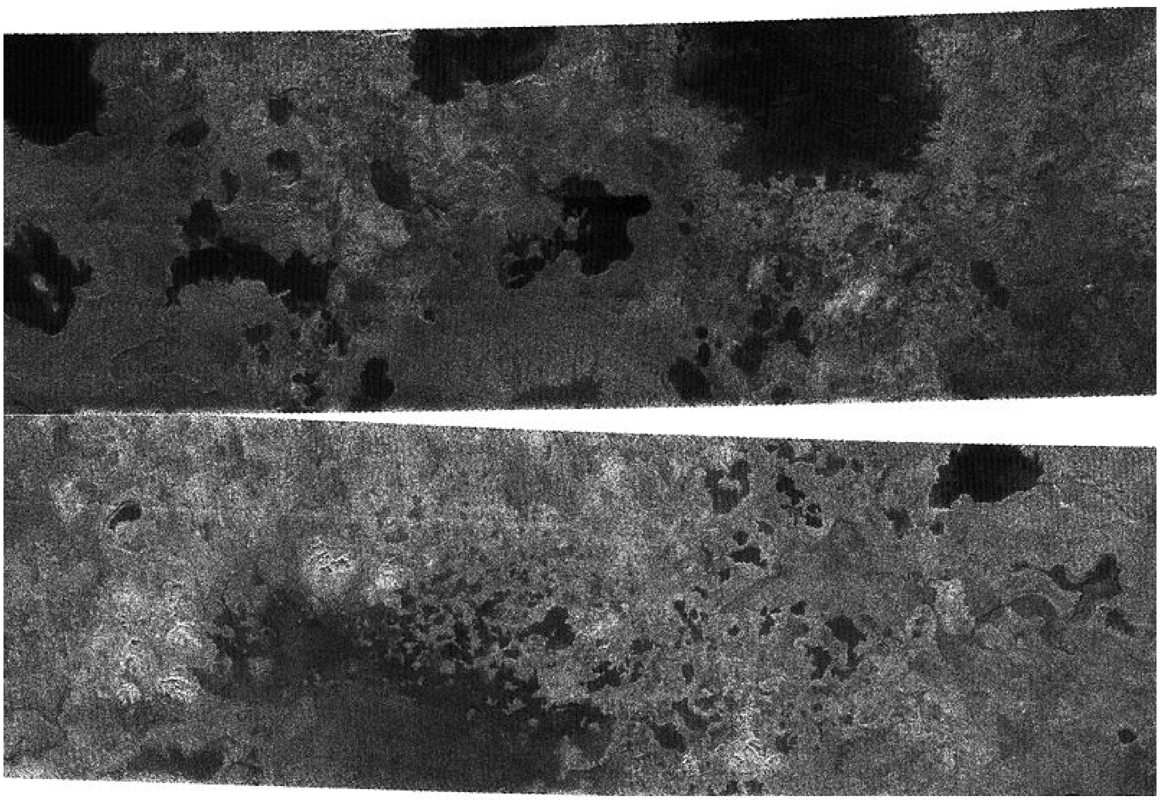
An eclipse of Saturn with the rings visible, taken in 2006

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

Spoke phenomenon verified

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

Lakes of Titan



Lakes of Titan

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

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

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

Saturn hurricane

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

Iapetus flyby

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

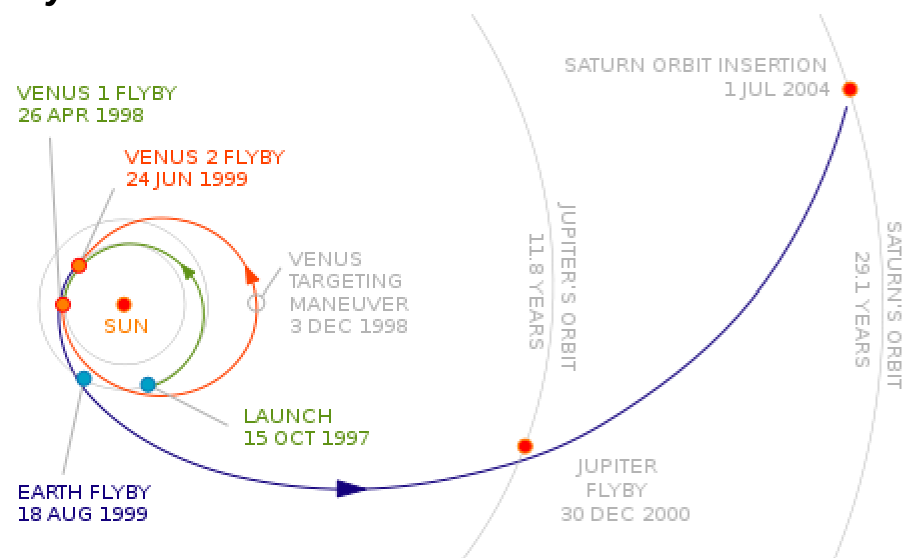
Mission extension

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

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

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

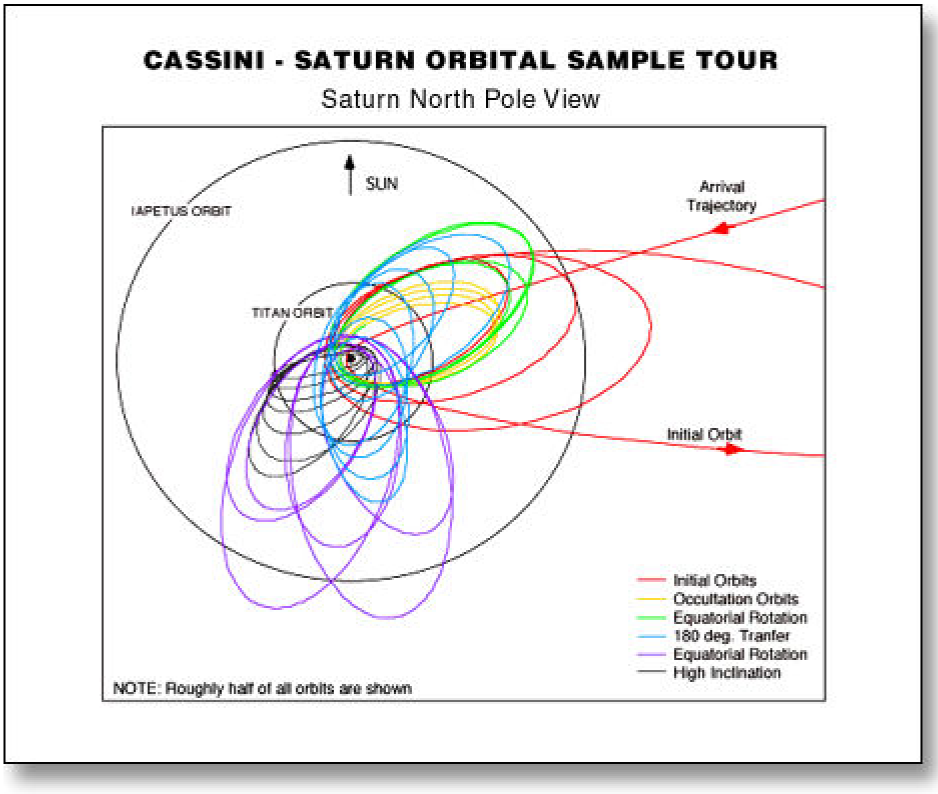
Trajectory



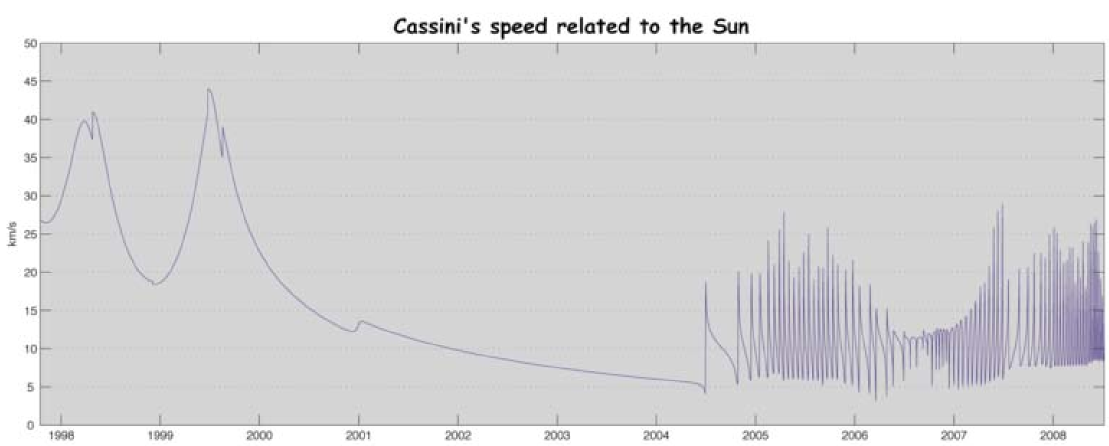
The initial gravitational-assist trajectory of *Cassini–Huygens*

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

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



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



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

Chapter- 7

Space and Solar System Exploration in 1998

Lunar Prospector

Lunar Prospector

Operator	NASA
Major contractors	Discovery Program
Mission type	Planetary Science
Satellite of	The Moon
Orbits	~7060
Launch date	1998-01-07, 02:28:44 UTC
Launch vehicle	Athena II

Mission duration	570 days
Mission highlight	Entered lunar orbit 1998-01-11, 10:28 UTC
COSPAR ID	1998-001A
Homepage	NASA NSSDC Master Catalog
Mass	158 kilograms (350 lb)
Orbital elements	
Semimajor axis	6,478.2 km (4,025.4 mi)
Eccentricity	0.00046
Inclination	90.55°
Apoapsis	101.2 km (62.9 mi)
Periapsis	99.45 km (61.80 mi)
Orbital period	117.9 minutes
Lunar landing	
Date	1999-07-31, 9:52:02 UTC
Coordinates	87°42′S 42°06′E / 87.7°S 42.1°E
Instruments	
Gamma ray spectrometer (GRS)	
Lunar prospector neutron spectrometer (NS)	
Alpha particle spectrometer (APS)	
Doppler gravity experiment (DGE)	
Magnetometer (MAG)	
Electron reflectometer (ER)	

The **Lunar Prospector** mission was the third selected by NASA for full development and construction as part of the Discovery Program. At a cost of $62.8 million, the 19-month mission was designed for a low polar orbit investigation of the Moon, including mapping of surface composition and possible polar ice deposits, measurements of magnetic and gravity fields, and study of lunar outgassing events. The mission ended July 31, 1999, when the orbiter was deliberately crashed into a crater near the lunar south pole in an unsuccessful attempt to detect the presence of water.

Data from the mission allowed the construction of a detailed map of the surface composition of the Moon, and helped to improve understanding of the origin, evolution, current state, and resources of the Moon. Several articles on the scientific results were published in the journal *Science*.

Lunar Prospector was managed out of NASA Ames Research Center with the prime contractor Lockheed Martin. The Principal Investigator for the mission was Dr. Alan Binder. His personal account of the mission *Against all Odds* is highly critical of the bureaucracy of NASA overall, and of its contractors.

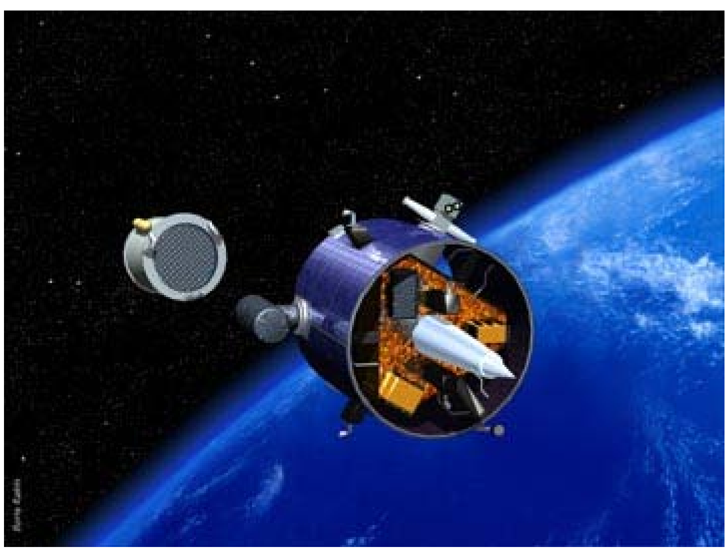
Spacecraft and subsystems

The fully assembled Lunar Prospector spacecraft is shown mated atop the Star 37 Trans Lunar Injection module

The spacecraft was a graphite-epoxy drum, 1.36 m (4.5 ft) in diameter and 1.28 m (4.2 ft) high with three radial 2.5 m (8.2 ft) instrument booms. A 1.1 m (3.6 ft) extension boom at the end of one of the 2.5 m booms held the magnetometer. Total initial mass (fully fueled) was 296 kg (650 lb). It was spin-stabilized (nominal spin rate 12 rpm) with its spin axis normal to the ecliptic plane. The spacecraft was controlled by six hydrazine monopropellant 22-newton thrusters (two aft, two forward, and two tangential). Three fuel tanks mounted inside the drum held 138 kg (300 lb) of hydrazine pressurized by helium. The power system consisted of body-mounted solar cells which produced an average of 186 W and a 4.8 A•h rechargeable NiCd battery. Communications were through two S-band transponders, a slotted, phased-array medium-gain antenna for downlink, and an omnidirectional low-gain antenna for downlink and uplink. The on-board computer was a Harris 80C86 with 64 kilobytes of EEPROM and 64 kilobytes of static RAM. All control was from the ground, the computer echoing each command to the ground for verification there. Once the command was ground-verified, an "execute" command from the ground told the computer to proceed with execution of the command. The computer built telemetry data as a combination of immediate data and also read from a circular queue buffer which allowed the computer to repeat data it had read 53 minutes earlier. This simple solid-state recorder ensured that all data collected during communications blackout periods would be received, providing the blackout was not longer than 53 minutes.

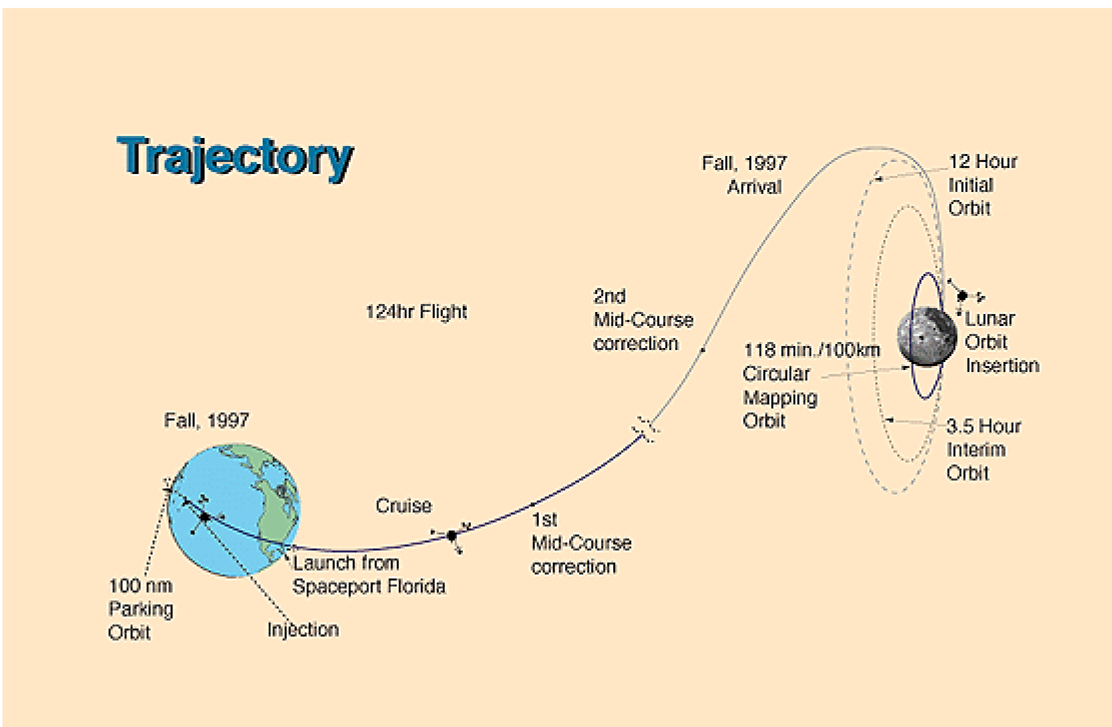
The probe also carried a small amount of the remains of Dr. Eugene Shoemaker (April 28, 1928 – July 18, 1997), astronomer and co-discoverer of Comet Shoemaker-Levy 9, to the moon for a space burial.

Mission profile



Artist's impression of NASA's Lunar Prospector probe leaving Earth orbit after separating from the booster fourth stage.

Following launch on January 7, 1998 UT (6 January EST) aboard a four-stage Athena II rocket, the Lunar Prospector had a 105 hour cruise to the Moon. During the cruise, the three instrument booms were deployed. The MAG and APS collected calibration data, while the GRS, NS, and ER outgassed for one day, after which they also collected calibration data in cis-lunar space. The craft was inserted into an 11.6-hour period capture orbit about the Moon at the end of the cruise phase. After 24 hours Lunar Prospector was inserted into a 3.5-hour period intermediate orbit, followed 24 hours later (on January 13, 1998) by transfer into a 92 km (57 mi) x 153 km (95 mi) preliminary mapping orbit, and then on 16 January by insertion into the near-circular 100 km (62 mi) altitude nominal lunar polar mapping orbit with an inclination of 90 degrees and a period of 118 minutes. Lunar calibration data was collected during the 11.6- and 3.5-hour orbits. Lunar mapping data collection started shortly after the 118 minute orbit was achieved. The data collection was periodically interrupted during the mission as planned for orbital maintenance burns, which took place to recircularize the orbit whenever the periselene or aposelene was more than 20 km (12 mi) to 25 km (16 mi) from the 100 km nominal orbit; this occurred about once a month. On December 19, 1998, a maneuver lowered the orbit to 40 km (25 mi) to perform higher resolution studies. The orbit was altered again on 28 January to a 15 km (9.3 mi) x 45 km (28 mi) orbit, ending the one year primary mission and beginning the extended mission.



Path of the Lunar Prospector space probe

The mission ended on July 31, 1999 at 9:52:02 UT (5:52:02 EDT) when Lunar Prospector was deliberately targeted to impact in a permanently shadowed area of the Shoemaker crater near the lunar south pole. It was hoped that the impact would liberate water vapor from the suspected ice deposits in the crater and that the plume would be detectable from Earth; however, no such plume was observed.

The Lunar Prospector mission was the third mission selected by NASA for full development and construction as part of NASA's Discovery Program. Total cost for the mission was $62.8 million including development ($34 million), launch vehicle (~$25 million) and operations (~$4 million).

Scientific experiments

The spacecraft carried six instruments: a Gamma Ray Spectrometer, a Neutron Spectrometer, a Magnetometer, an Electron Reflectometer, an Alpha Particle Spectrometer, and a Doppler Gravity Experiment. The instruments were omnidirectional and required no sequencing. The normal observation sequence was to record and downlink data continuously.

Gamma Ray Spectrometer (GRS)

The Lunar Prospector GRS produced the first global measurements of gamma-ray spectra from the lunar surface, from which are derived the first "direct" measurements of the chemical composition for the entire lunar surface. This data effectively maps the distribution of various important elements across the Moon. For example, the Lunar Prospector GRS has identified several regions with high iron concentrations.

The fundamental purpose of the GRS experiment was to provide global maps of elemental abundances on the lunar surface. The GRS was designed to record the spectrum of gamma rays emitted by:

1. the radioactive decay of elements contained in the Moon's crust; and
2. elements in the crust bombarded by cosmic rays and solar wind particles.

The most important elements detectable by the GRS were uranium (U), thorium (Th), and potassium (K), radioactive elements which generate gamma rays spontaneously, and iron (Fe), titanium (Ti), oxygen (O), silicon (Si), aluminum (Al), magnesium (Mg), and calcium (Ca), elements which emit gamma rays when hit by cosmic rays or solar wind particles. The uranium, thorium, and potassium in particular were used to map the location of KREEP (potassium, rare-earth element, and phosphorus containing material, which is believed to have developed late in the formation of the crust and upper mantle, and is therefore important to understanding lunar evolution). The GRS was also capable of detecting fast (epithermal) neutrons, which complemented the neutron spectrometer in the search for water on the Moon.

The Gamma Ray Spectrometer was a small cylinder which was mounted on the end of one of the three 2.5 m (8.2 ft) radial booms extending from the Lunar Prospector. It consisted of a bismuth germanate crystal surrounded by a shield of borated plastic. Gamma rays striking the bismuth atoms produced a flash of light with an intensity proportional to the energy of the gamma ray which was recorded by detectors. The energy of the gamma ray is associated with the element responsible for its emission. Due to a low signal-to-noise ratio, multiple passes were required to generate statistically significant results. At nine passes per month, it was expected to take about three months to confidently estimate abundances of thorium, potassium, and uranium, and 12 months for the other elements. The precision varies according to element measured. For U, Th, and K, the precision is 7% to 15%, for Fe 45%, for Ti 20%, and for the overall distribution of KREEP 15% to 30%. The borated plastic shield was used in the detection of fast neutrons. The GRS was designed to achieve global coverage from an altitude of approximately 100 km (62 mi) and with a surface resolution of 150 km (93 mi).

Neutron Spectrometer (NS)

Based on Lunar Prospector Neutron Spectrometer (NS) data, mission scientists have determined that there is indeed water ice in the polar craters of the Moon, an estimated 3 billion metric tons (260 billion US gallons).

The NS was designed to detect minute amounts of water ice which were believed to exist on the Moon. It was capable of detecting water ice at a level of less than 0.01%. The Moon has a number of permanently shadowed craters near the poles with continuous temperatures of −190 °C (−310.0 °F). These craters may act as cold-traps of water from incoming comets and meteoroids. Any water from these bodies which found its way into these craters could become permanently frozen. The NS was also used to measure the abundance of hydrogen implanted by solar wind.

The neutron spectrometer was a thin cylinder colocated with the Alpha Particle Spectrometer at the end of one of the three radial Lunar Prospector science booms. The instrument had a surface resolution of 150 km (93 mi). For the polar ice studies, the NS was slated to examine the poles to 80 degrees latitude, with a sensitivity of at least 10 ppm by volume of hydrogen. For the implanted hydrogen studies, the NS was intended to examine the entire globe with a sensitivity of 50 ppmv. The neutron spectrometer consisted of two canisters each containing helium-3 and an energy counter. Any neutrons colliding with the helium atoms give an energy signature which can be detected and counted. One of the canisters was wrapped in cadmium, and one in tin. The cadmium screens out thermal (low energy or slow-moving) neutrons, while the tin does not. Thermal neutrons are cosmic-ray-generated neutrons which have lost much of their energy in collisions with hydrogen atoms. Differences in the counts between the two canisters indicate the number of thermal neutrons detected, which in turn indicates the amount of hydrogen on the Moon's crust at a given location. Large quantities of hydrogen would likely be due to the presence of water.

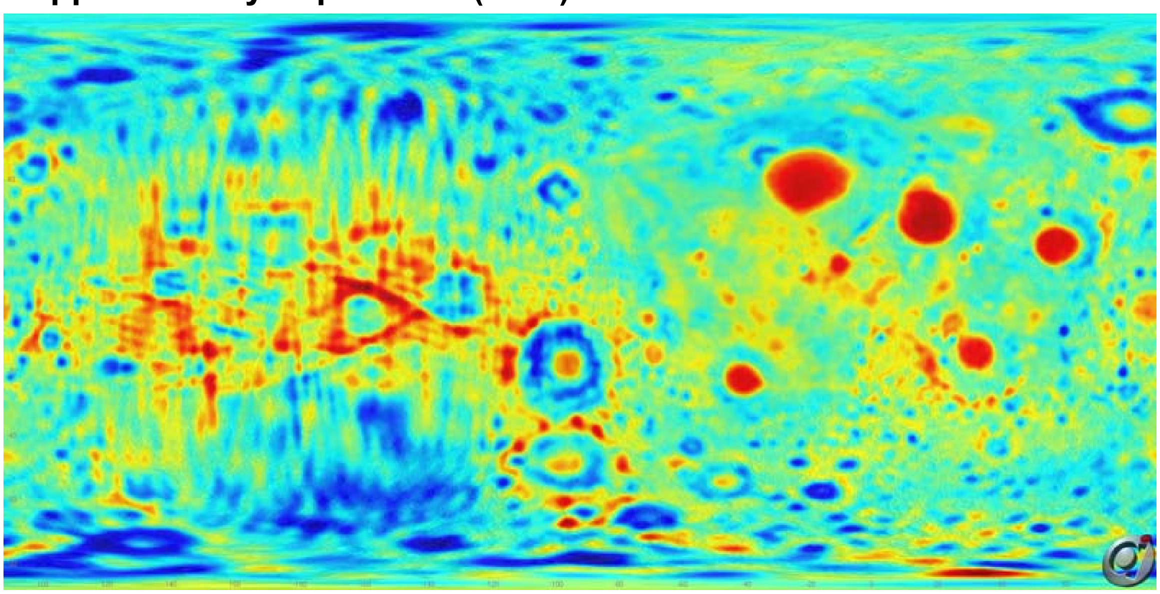
The Alpha Particle Spectrometer (APS)

The Alpha Particle Spectrometer (APS) was damaged during launch, ruining one of the five detecting faces. Additionally, due to sunspot activity peaking during the mission, the lunar data is obscured by solar interference. NASA has stated that the information can eventually be recovered by subtracting out the effects of the solar activity. In the meantime, however, the APS has not yielded any useful results.

The APS was designed to detect radon outgassing events on the surface of the Moon. The APS recorded alpha particle signatures of radioactive decay of radon gas and its daughter product, polonium. These putative outgassing events, in which radon, nitrogen, and carbon dioxide are vented, are hypothesized to be the source of the tenuous lunar atmosphere, and may be the result of the low-level volcanic/tectonic activity on the Moon. Information on the existence, timing, and sources of these events may help in a determination of the style and rate of lunar tectonics.

The APS was a cube approximately 18 cm (7.1 in) on a side colocated with the neutron spectrometer on the end of one of the three radial 2.5 m (8.2 ft) Lunar Prospector science booms. It contained ten silicon detectors sandwiched between gold and aluminum disks arranged on five of six sides of the cube. Alpha particles, produced by the decay of radon and polonium, leave tracks of charge on the silicon wafers when they impact the silicon. A high voltage is applied to the silicon, and the current is amplified by being funneled along the tracks to the aluminum disk and is recorded for identification. The APS was designed to make a global examination of gas release events and polonium distribution with a surface resolution of 150 km (93 mi) and a precision of 10%.

Doppler Gravity Experiment (DGE)



A visualization of the lunar gravity field based on spherical harmonic coefficients determined from Lunar Prospector data. The left side of the image shows the far of the moon where the increased uncertainty in the gravity field can be seen.

The Doppler Gravity Experiment (DGE) was the first polar, low-altitude mapping of the lunar gravity field. The Clementine mission had previously produced a relatively low-resolution map, but the Prospector DGE obtained data approximately five times as detailed: the "first truly operational gravity map of the Moon". The practical benefits of this are more stable long-term orbits and better fuel efficiency. Additionally, the DGE data is hoped to help researchers learn more about lunar origins and the nature of the lunar core. The DGE has identified three new near-side mascons (mass concentrations).

The purpose of the Lunar Prospector DGE was to learn about the surface and internal mass distribution of the Moon. This is accomplished by measuring the Doppler shift in the S-band tracking signal as it reaches Earth, which can be converted to spacecraft accelerations. The accelerations can be processed to provide estimates of the lunar gravity field, from which the location and size of mass anomalies affecting the spacecraft orbit can be modeled. Estimates of the surface and internal mass distribution give information on the crust, lithosphere, and internal structure of the Moon.

This experiment provided the first lunar gravity data from a low polar orbit. Because line-of-sight tracking is required for this experiment, only the near-side gravity field could be estimated using this Doppler method. The experiment is a byproduct of the spacecraft S-band tracking, and so has no listed weight or power requirements. The experiment was designed to give the near-side gravity field with a surface resolution of 200 km (120 mi) and precision of 5 mGal (0.05 mm/s^2) in the form of spherical harmonic coefficients to degree and order 60. In the extended mission, in which the spacecraft descended to an orbit with an altitude of 50 km (31 mi) and then to 10 km (6.2 mi), this resolution was expected to improve by a factor of 100 or more.

The downlink telemetry signal was transmitted at 2273 MHz, over a ±1 MHz bandwidth as a right-hand circularly polarized signal at a nominal power of 5 W and peak power of 7 W. Command uplinks were sent at 2093.0542 MHz over a ±1 MHz bandwidth. The transponder was a standard Loral/Conic S-Band transponder. An omnidirectional antenna can be used for uplink and downlink, or a medium gain helix antenna can be used (downlink only). Since the spacecraft was spin-stabilized, the spin resulted in a bias in the Doppler signal due to the spacecraft antenna pattern spinning with respect to the Earth station of 0.417 Hz (27.3 mm/s) for the omnidirectional antenna, and −0.0172 Hz (−1.12 mm/s) for the medium gain antenna. LOS data was sampled at 5 seconds to account for the approximately 5 second spin rate of the spacecraft, leaving a residual of less than 0.1 mm/s.

Electron Reflectometer and Magnetometer (MAG/ER)

The Magnetometer and Electron Reflectometer (collectively, MAG/ER) detected anomalous surface magnetic fields on the Moon, which are in stark contrast to a global magnetosphere (which the Moon lacks). The Moon's overall magnetic field is too weak to deflect the solar wind, but MAG/ER discovered a small surface anomaly that can do so. This anomaly, about 100 km (62 mi) in diameter, has therefore been referred to as "the smallest known magnetosphere, magnetosheath and bow shock system in the Solar System". Due to this and other magnetic features of the Moon's surface, hydrogen deposited by solar wind is non-uniformly distributed, being denser at the periphery of the magnetic features. Since hydrogen density is a desirable characteristic for hypothetical lunar bases, this information may be useful in choosing optimal sites for possible long-term Moon missions.

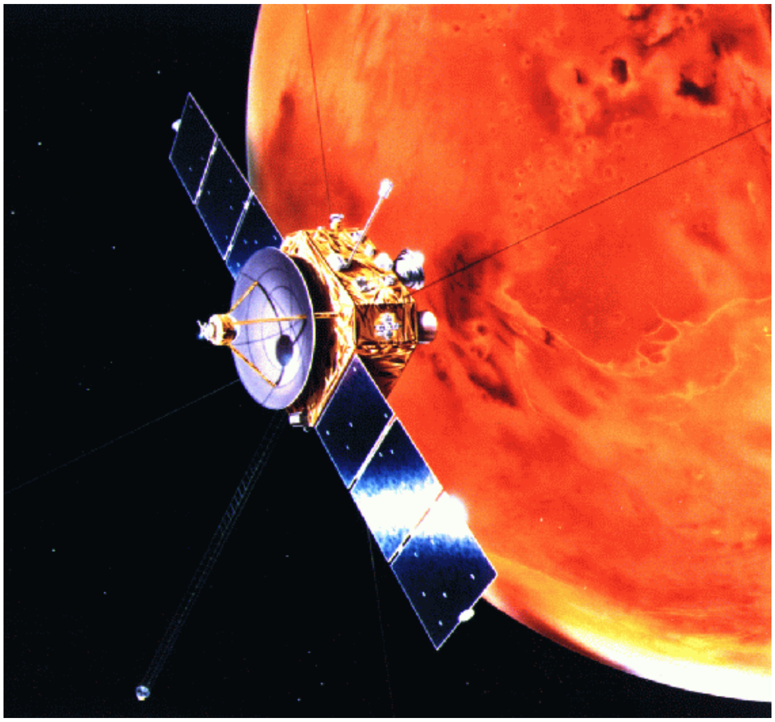
The electron reflectometer (ER) and magnetometer (MAG) were designed to collect information on the lunar magnetic fields. The Moon has no global magnetic field, but it does have weak localized magnetic fields at its surface. These may be paleomagnetic remnants of a former global magnetic field, or may be due to meteor impacts or other local phenomena. This experiment was to help map these fields and provide information on their origins, allow possible examination of distribution of minerals on the lunar surface, aid in a determination of the size and composition of the lunar core, and provide information on the lunar induced magnetic dipole.

The ER determined the location and strength of magnetic fields from the energy spectrum and direction of electrons. The instrument measured the pitch angles of solar wind electrons reflected from the Moon by lunar magnetic fields. Stronger local magnetic fields can reflect electrons with larger pitch angles. Field strengths as small as 0.01 nT could be measured with a spatial accuracy of about 3 km (1.9 mi) at the lunar surface. The MAG was a triaxial fluxgate magnetometer similar in design to the instrument used on Mars Global Surveyor. It could measure the magnetic field amplitude and direction at spacecraft altitude with a spatial resolution of about 100 km (62 mi) when ambient plasma disturbances are minimal.

The ER and the electronics package were located at the end of one of the three radial science booms on Lunar Prospector. The MAG was in turn extended further on a 0.8 m (2.6 ft) boom—a combined 2.6 m (8.5 ft) from the Lunar Prospector in order to isolate it from spacecraft generated magnetic fields. The ER and MAG instruments had a combined mass of 5 kg (11 lb) and used 4.5 watts of power.

Nozomi

Nozomi



Nozomi at Mars

Operator	JAXA
Mission type	Orbiter
Satellite of	Mars
Launch date	July 3, 1998, Uchinoura Space Center
Launch vehicle	M-V
Mission duration	December 9, 2003
COSPAR ID	1998-041A
Homepage	Nozomi official site
Mass	258 kilograms (570 lb)

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

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

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

Mission profile

Launch

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

Lunar swing-bys

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

Earth swing-by

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

New mission plan

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

First Earth flyby

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

Second Earth flyby

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

Mars flyby

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

Intended Mars mission

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

Spacecraft and subsystems

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

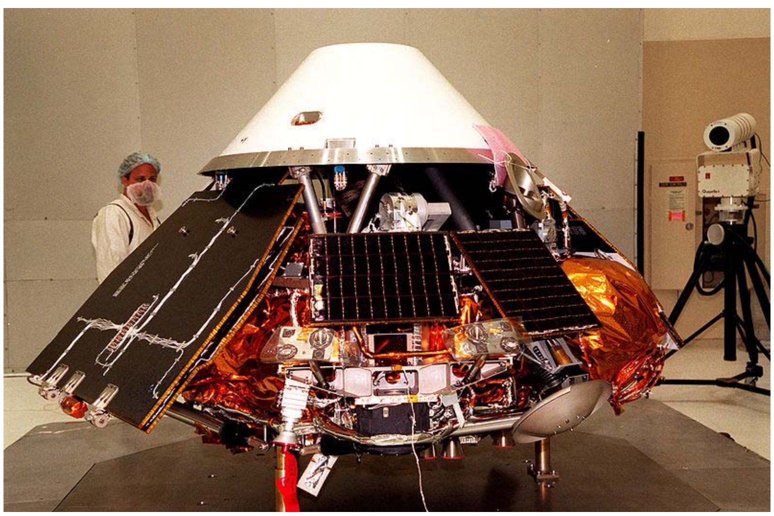
Canada provided a $5 million thermal plasma analyser. This was the Canadian Space Agency's first participation in an interplanetary mission.

Chapter- 8

Space and Solar System Exploration in 1999

Mars Polar Lander

Mars Polar Lander



Operator	NASA / JPL
Major contractors	Russian Space Research Institute
Mission type	Lander / impactor
Launch date	1999-01-03 20:21:10 UTC
Launch vehicle	Delta II 7425
Launch site	Space Launch Complex 17B Cape Canaveral Air Force Station
Mission duration	(failure in transit) Last contact on day 334

	1999-12-03 20:00:00 UTC
Landing site	Ultimi Scopuli, 76°S 195°W / 76°S 195°W (projected)
COSPAR ID	1999-001A
Mass	290 kg (640 lb)
Power	200 W (Solar array/NiMH batteries)
	Instruments
Main instruments	Deep Space 2 probes MVACS MARDI LIDAR

Mars Polar Lander (sometimes referred to as the ***Mars Surveyor '98 Lander***) is one of two exploration vehicles of the NASA Mars Surveyor '98 program. Launched on 3 January 1999, 23 days after its partner, the *Mars Climate Orbiter*, the mission ended in failure with the loss of both craft in separate incidents. After attempts to re-establish communications failed following entry into Mars atmosphere, the lander was declared lost, with the presumption that the vehicle did not survive the descent.

Scientific objectives

Conveyed on the *Mars Polar Lander* was the *Deep Space 2* surface-penetrator mission to Mars. The two missions were designed to study the Martian weather, climate, water and carbon dioxide concentrations, in order to understand the reservoirs, behavior, and atmospheric role of volatiles and to search for evidence of long-term and episodic climate changes.

The lander was to touch down on the southern polar layered terrain, between 73°S and 76°S in the region Planum Australe, less than 1,000 km from the south pole, near the edge of the carbon dioxide ice cap in Mars' late southern spring. The terrain appears to be composed of alternating layers of clean and dust-laden ice, and may represent a long-term record of the climate, as well as an important volatile reservoir.

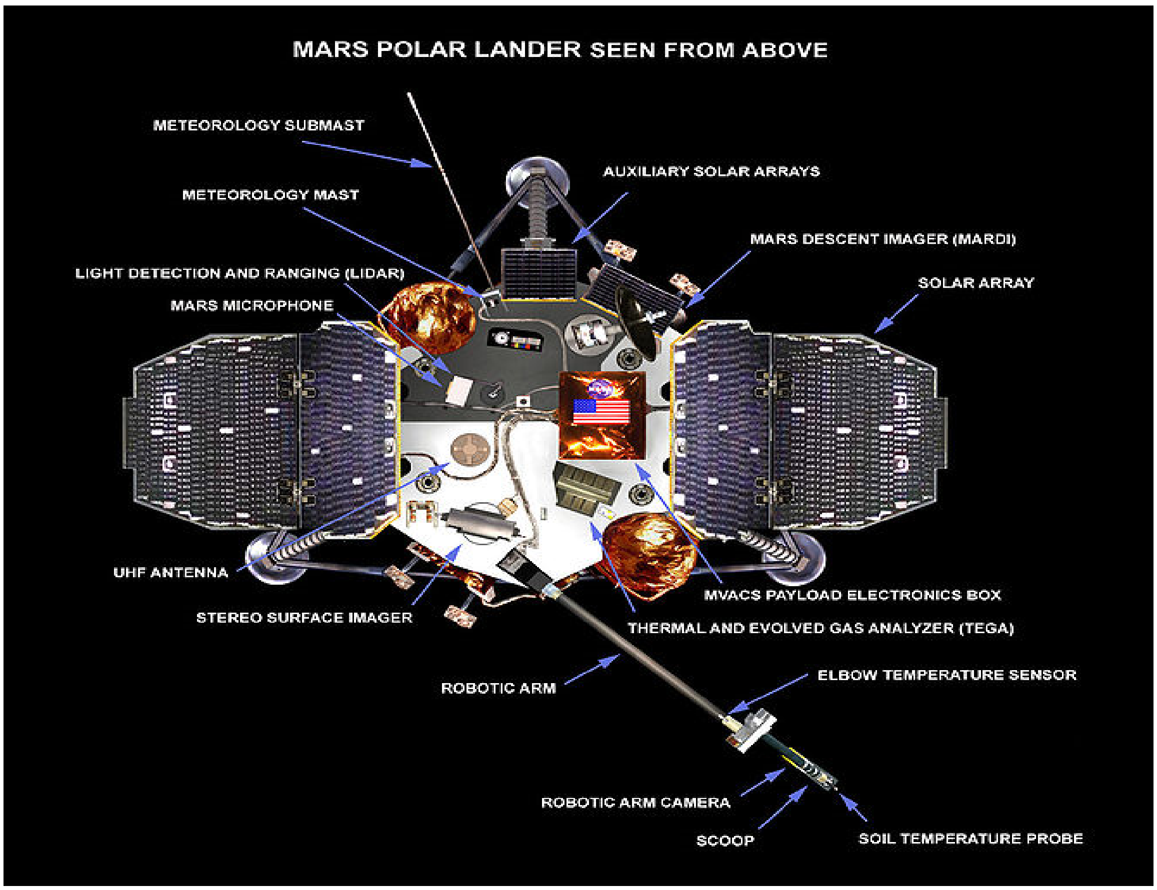
Mission science objectives

- Log local meteorological conditions near the martian south pole, including temperature, pressure, humidity, wind, surface frost, ground ice evolution, ice fogs, haze, and suspended dust
- Analyze samples of the polar deposits for volatiles, particularly water and carbon dioxide

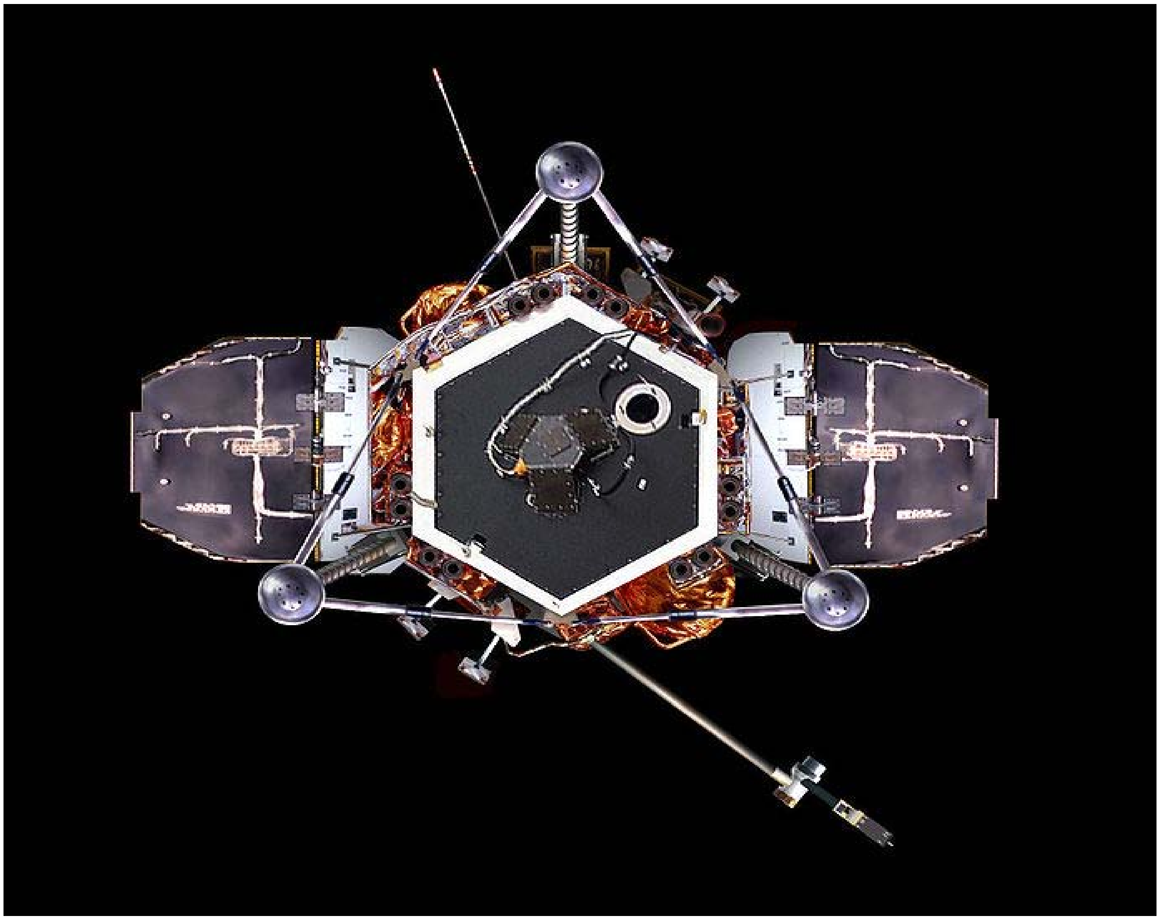
- Excavate trenches and image the interior to look for seasonal layers and analyze soil samples for water, ice, hydrates, and other aqueously deposited minerals
- Image the regional and immediate landing site surroundings for evidence of climate changes and seasonal cycles
- Obtain multi-spectral images of local regolith to determine soil types and composition.

These goals were to be accomplished using a number of scientific instruments, including a Mars Volatiles and Climate Surveyor (MVACS) instrument package which was composed of a robotic arm and attached camera, mast-mounted surface stereo imager and meteorology package, and a gas analyzer. In addition, a Mars Descent Imager (MARDI) was planned to capture regional views from parachute deployment at about 5 miles (8 km) altitude down to the landing. The Russian Space Agency provided a laser ranger (LIDAR) package for the lander, which would be used to measure dust and haze in the Martian atmosphere. A miniature microphone would also be on board to record sounds on Mars. Attached to the lander spacecraft were a pair of small probes, the Deep Space 2 Mars Microprobes, which were to be deployed to fall and penetrate beneath the martian surface when the spacecraft reached Mars.

Spacecraft and subsystems



Mars Polar Lander viewed from above



Mars Polar Lander viewed from below

The *Mars Polar Lander* consisted of a hexagonal base composed of aluminum honeycomb with composite graphite epoxy face sheets supported on three aluminum landing legs. The lander, when fully deployed stood 1.06 m tall and approximately 3.6 m wide. The launch mass of the spacecraft was approximately 583 kg, including 64 kg of fuel, an 82 kg cruise stage, a 140 kg aeroshell/heatshield, and the two 3.5 kg microprobes. A thermally regulated interior component deck held temperature-sensitive electronic components and batteries and the thermal control system. Two solar panels extended from opposite sides of the base. Mounted on top of the base were the robotic arm, the stereo imager and mast, a UHF antenna, the LIDAR, the MVACS electronics, the meteorology mast, and the medium-gain dish antenna. The MARDI was mounted at the base of the lander, and the propellant tanks were affixed to the sides. During cruise, the lander was attached to the cruise stage and enclosed in the 2.4 m diameter aeroshell.

The spacecraft was three-axis stabilized during cruise using star cameras and sun sensors in conjunction with inertial measurement units. Four hydrazine cruise reaction engine modules, each consisting of one 5-lb_f (22 N) trajectory correction maneuver thruster and one canted 1-lb_f (4 N) reaction control system thruster, provided attitude control. The descent and landing propulsion system consisted of three groups of four pulse-modulated 266 N hydrazine engines. Control and knowledge for descent and landing was provided by a four-beam Doppler radar system and an AACS subsystem. The hydrazine was stored in two diaphragm tanks with a total capacity of 64 kg for both cruise and descent systems.

Communications between Earth and the spacecraft during cruise to Mars were via X band using two solid state power amplifiers and a fixed medium-gain antenna mounted on the cruise stage and backed up by a receive-only low-gain antenna. During surface operations communications (downlink and uplink) would have been via the UHF antenna on the lander to the Mars Climate Orbiter, which would function as a relay to Earth. Eight to ten relay passes over the lander would have been available from the orbiter each day, but the number of communications sessions would be limited by power demands. Uplink-only communications to Earth were to be provided by the medium-gain DTE (direct to Earth) two-axis articulated antenna.

Power was provided during cruise phase by two gallium arsenide solar array wings with a total area of 3.1 m^2 attached to the cruise stage. After landing, two gallium arsenide solar array wings with a total area of 2.9 m^2 would have been deployed. Power is stored in 16 A·h nickel metal hydride common pressure vessel batteries for peak load operations and night time heating. The payload is allocated 25 W of continuous power when operating.

Mission profile

Mars Polar Lander and the attached *Deep Space 2* probes were launched on a Delta II 7425 lite launch vehicle with four strap-on solid-rocket boosters and a Star 48 (PAM-D) third stage, which placed them into a low-Earth parking orbit. The third stage fired for 88 seconds at 20:57 UT 3 January 1999 to put the spacecraft into a Mars transfer trajectory and the spacecraft and third stage separated at 21:03 UT. Trajectory correction maneuvers were performed on 21 January, 15 March, 1 September, 30 October, and 30 November 1999.

After an 11-month hyperbolic transfer cruise, the *Mars Polar Lander* reached Mars on 3 December 1999. A final 30 minute tracking session began at 12:45 UT (7:45 a.m. EST) and was used to determine if a final thruster correction was necessary. Final contact to retrieve data on the status of the propulsion system was made from 19:45 UT to 20:00 UT. At 20:04, 6 minutes before atmospheric entry, an 80 second thruster firing was to turn the craft to its entry orientation. The cruise stage was to be jettisoned at about 20:05 UT, and about 18 seconds later the microprobes were to be dropped from the cruise stage into the martian atmosphere (also targeted at the southern polar layered terrain). The lander was to make a direct entry into Mars' atmosphere at 6.8 km/s at about 20:10 UT (3:10 p.m. EST). Because of lack of communication, it is not known at this time whether all these steps following last contact were executed, nor whether any of the descent plan described below took place as designed.

Initial deceleration would be simple aerobraking using the 2.4 m ablation heat shield. The maximum time from atmospheric entry to landing would be 4 minutes 33 seconds. The inertial measurement unit would estimate the velocity throughout the entry and descent phase and the thrusters would keep the craft aligned. At an altitude of about 7.3 km at 500 m/s the parachute would be deployed by a mortar followed by heat shield separation. Just before heat shield separation, the descent imager (MARDI) would turn on. The landing legs would be deployed 70 to 100 seconds before landing and the descent engines warmed up with short pulses. Then the parachute would be jettisoned and the descent engines fired, regulated by the spacecraft control system and the Doppler radar. The backshell would separate from the lander at about 1.4 km altitude at 80 m/s and the descent engines turned on to slow the descent and turn the flight path to vertical.

At 12 meters altitude the 2.4 m/s terminal descent phase was to begin. Engine shutoff would occur when one of the landing legs touched the ground. The landing velocity would be less than 2.4 m/s vertical and 1 m/s horizontal. The orientation of the lander is controlled by the AACS subsystem to maximize solar array efficiency and minimize obstruction of the DTE antenna. The lander would have touched down at 20:15 UT Earth received time (3:15 p.m. EST) in the late southern spring season, during which the Sun will always be above the horizon at the landing site. The other times listed above are also Earth received times; light travel time from Mars at that point was approximately 14 minutes.

Immediately after landing the solar panels were to be deployed. The first signal from the lander was to reach Earth at 20:39 UT (3:39 p.m. EST), but was never received. This was to be the start of a 45 minute communications session. After this session the lander was to recharge its batteries for about six hours. On 4 December at 04:30 UT (11:30 p.m. EST December 3) a communications session was to begin which would have lasted about 2.25 hours. This session would have included images, including pictures from the Mars Descent Imager, but again no transmission was received. The first sounds from the Mars Microphone were to be released as early as 4 December and the first robot arm dig was to occur on 7 December. Science experiments would continue over the 90-day primary mission, with an extended mission to follow based on lander performance.

Mission failure

The last telemetry from the *Mars Polar Lander* was sent just prior to atmospheric entry on December 3, 1999. No further signals have been received from the lander. The cause of the communication loss is not known. The investigation that followed concluded that the most likely cause of the failure of the mission was a software error that mis-identified vibrations caused by the deployment of the lander's legs as vehicle touch-down on the Martian surface. The resulting action was the shut-down of the vehicle's descent engines while still 40 meters aloft. Although it was known that leg deployment could create the false indication, the software's design instructions did not account for that eventuality.

In addition to the premature shutdown of descent engines, the following failure modes were also assessed as plausible by the Failure Review Board convened to study the loss of Mars Polar Lander and Deep Space 2. Although thought less likely than the premature engine shutdown, they could not be ruled out due to the lack of telemetry.

- Surface conditions exceed landing design capabilities.
- Loss of control due to dynamic effects.
- Landing site not survivable.
- Backshell/parachute contacts lander.
- Loss of control due to center-of-mass offset.
- Heatshield fails due to micrometeoroid impact.

Attempts were made in late 1999 and early 2000 to search for the remains of the *Mars Polar Lander* using images from the *Mars Global Surveyor*. These attempts were unsuccessful, but re-examination of the images in 2005 led to a tentative identification described in the July 2005 issue of *Sky and Telescope*. However, higher resolution photos taken later in 2005 revealed that this identification was incorrect, and that the *Mars Polar Lander* remains lost. NASA is hoping that the higher resolution cameras of the *Mars Reconnaissance Orbiter*, currently in Martian orbit, will finally locate the lander's remains.

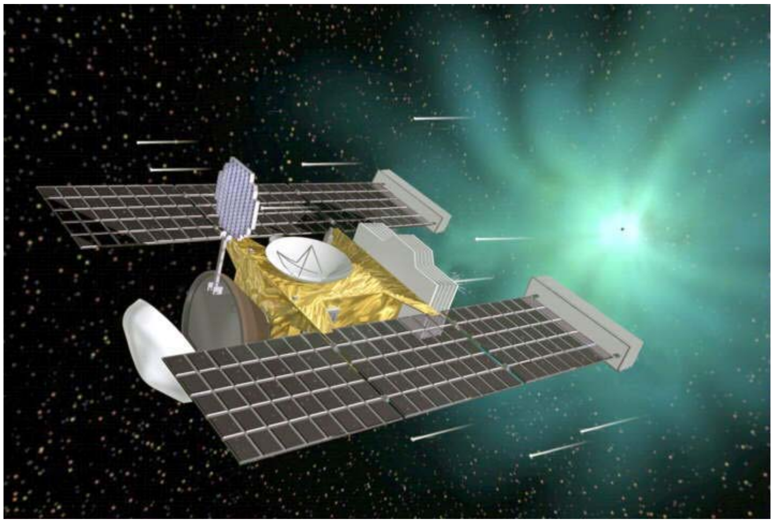
Legacy

The *Phoenix* spacecraft successfully landed on May 25, 2008, carrying some instruments derived from those on the *Mars Polar Lander*.

The failure of the Mars Polar Lander took place two and a half months after the loss of the Mars Climate Orbiter. Inadequate funding and poor management have been cited as underlying causes of the failures. According to Thomas Young, chairman of the Mars Program Independent Assessment Team, the program "was under funded by at least 30%."

Stardust

Stardust



Artist's conception of the Stardust spacecraft

Operator	NASA / JPL
Major contractors	Lockheed Martin
Mission type	Flyby, Sample return
Satellite of	Sun
Launch date	1999-02-07 21:04:15 UTC (11 years, 11 months, and 9 days ago)
Launch vehicle	Delta II 7426
Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
Mission duration	In progress (NeXT) (8 years, 2 months, and 14 days elapsed) Annefrank flyby *(completed 2002-11-02)* Wild 2 flyby *(completed 2004-01-02)* Sample return *(completed 2006-01-15)* Primary mission

	(completed 2006-01-15)
	Tempel 1 flyby
	(projected 2011-02-14)
Landing site	Utah Test and Training Range
COSPAR ID	1999-003A
Mass	300 kg (661 lb)
Power	330 W (Solar array / NiH_2 batteries)

Stardust is an American interplanetary mission of the NASA Jet Propulsion Laboratory, whose primary purpose was to investigate the makeup of the comet Wild 2 and its coma. It was launched on February 7, 1999 by NASA, traveled nearly 3 billion miles ($5\cdot10^9$ km), and returned to Earth on January 15, 2006 to release a sample material capsule. It is the first sample return mission to collect cosmic dust and return the sample to Earth. On July 3, 2007 a second mission was approved to revisit the comet Tempel 1.

Primary mission

NASA began construction of the Stardust spacecraft in 1996. After launch on feb 04,1999, the Stardust spacecraft travelled in an initial orbit beyond — but intersecting — Earth's orbit. The Delta II booster did not have enough energy to reach Wild 2 directly. The Stardust spacecraft then approached Earth in January 2001 for a gravity assist maneuver. The encounter with Earth enlarged the spacecraft's orbit to intersect that of Wild 2.

On the second orbit, Stardust flew by the comet Wild 2 on January 2, 2004. During the flyby it collected dust samples from the comet's coma and took detailed pictures of its icy nucleus. Additionally, the spacecraft accomplished several other goals. It passed within 3300 km of the asteroid 5535 Annefrank on November 2, 2002 and took several photographs. The aerogel collector also acquired interstellar dust. In March-May 2000 and July-December 2002, the spacecraft angled itself into a dust stream believed to originate outside the solar system. The reverse side of the aerogel collector then caught a sample of such particles.

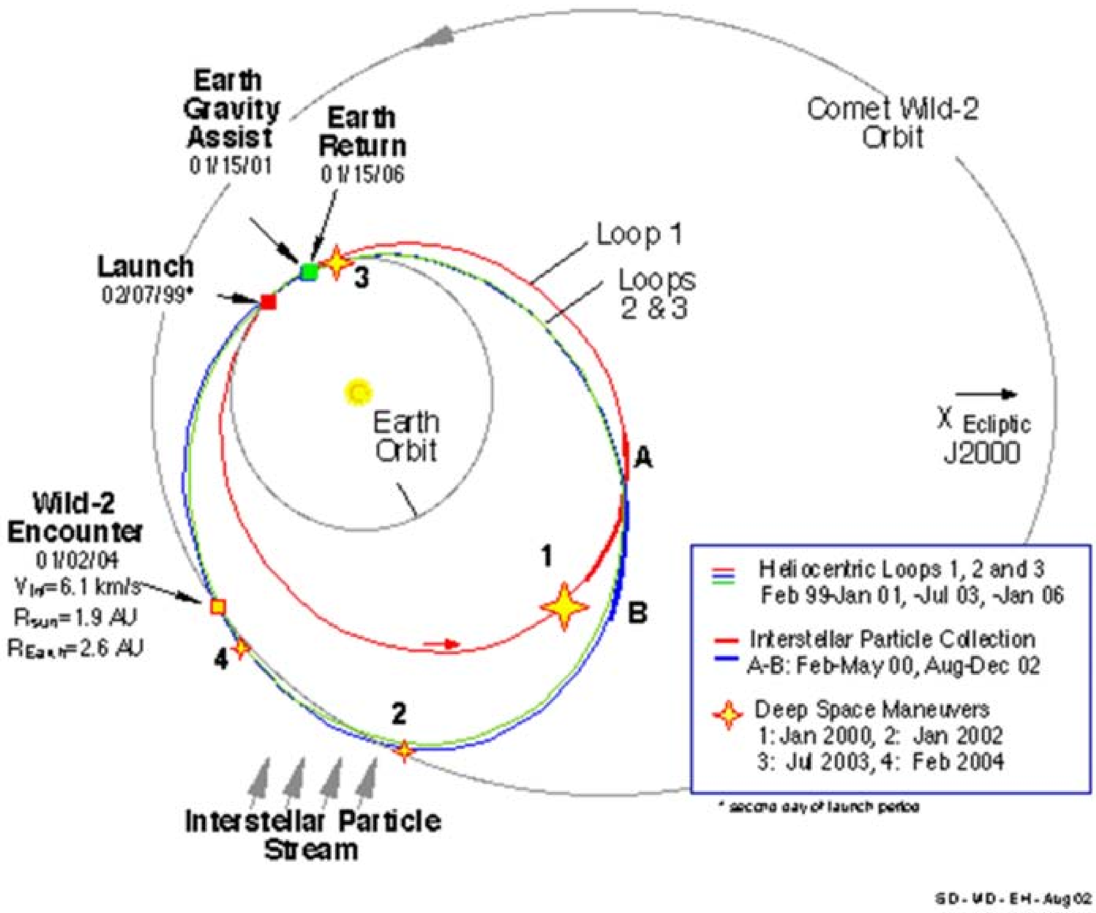
The sample material capsule from Stardust returned to Earth at approximately 10:10 UTC on January 15, 2006 in Utah's Great Salt Lake desert, near the U.S. Army Dugway Proving Ground, to deliver the sample material. The landing coordinates were 40°21.9′N 113°31.25′W / 40.365°N 113.52083°W. Winds had blown the capsule a few miles off its ballistic trajectory, but it was within the target area. On arrival, the capsule was traveling in a nearly flat trajectory, at 12.9 km/s (28,900 miles per hour), which is the fastest re-entry speed into Earth's atmosphere ever achieved by a man-made object. As a point of comparison, NASA stated it would be able to travel from Salt Lake City, Utah to

New York City, New York in less than six minutes. A large fire ball and sonic boom were observed in western Utah and eastern Nevada.

The Stardust space probe had been put into a "divert maneuver" to keep the hardware from hitting Earth. Under twenty kilograms of fuel remained onboard after the maneuver. On January 29, the craft was put in hibernation mode with only its solar panels and receiver still active in a three-year heliocentric orbit that would return it to Earth's vicinity on January 14, 2009.

Donald Brownlee, from the University of Washington, was the Principal Investigator for the Stardust mission. Ken Atkins of the Jet Propulsion Laboratory managed the project during development. Joe Vellinga was the Program Manager at the spacecraft contractor, Lockheed Martin. The Project Manager during Stardust operations and the current Project Manager for the NExT secondary mission is Tom Duxbury of the Jet Propulsion Laboratory.

The Stardust capsule after reentry (January 15, 2006)



Stardust trajectory

Reentry of Stardust filmed from a NASA aircraft

Secondary mission: New Exploration of Tempel 1 (NExT)

On 19 March 2006 Stardust scientists announced that they were considering the possibility of redirecting the spacecraft on a secondary mission to photograph Tempel 1, the comet that was impacted by the Deep Impact spacecraft in 2005. This possibility is important because Deep Impact did not succeed in capturing a good image of the crater formed on Tempel 1, due to obscuring dust from the impact.

On July 3, 2007 this extended mission was approved, under the designation of *New Exploration of Tempel 1* (NExT). This investigation will provide the first look at the changes to a comet nucleus produced after its close approach to the sun. NExT also will extend the mapping of Tempel 1, making it the most mapped comet nucleus to date. This mapping will help address the major questions of comet nucleus "geology" raised by images of areas where it appears material might have flowed like a liquid or powder. NExT is scheduled to fly by Tempel 1 on February 15, 2011 at 04:42 GMT.

The craft

Stardust launch preparations

The mission spacecraft is derived from the Space probe deep space bus developed by Lockheed Martin Astronautics. This new lightweight spacecraft incorporates components, virtually all of which are either currently operating in space or are flight qualified and manifested to fly on upcoming missions. Several components have heritage from the Cassini mission; some were developed under the Small Spacecraft Technologies Initiative (SSTI).

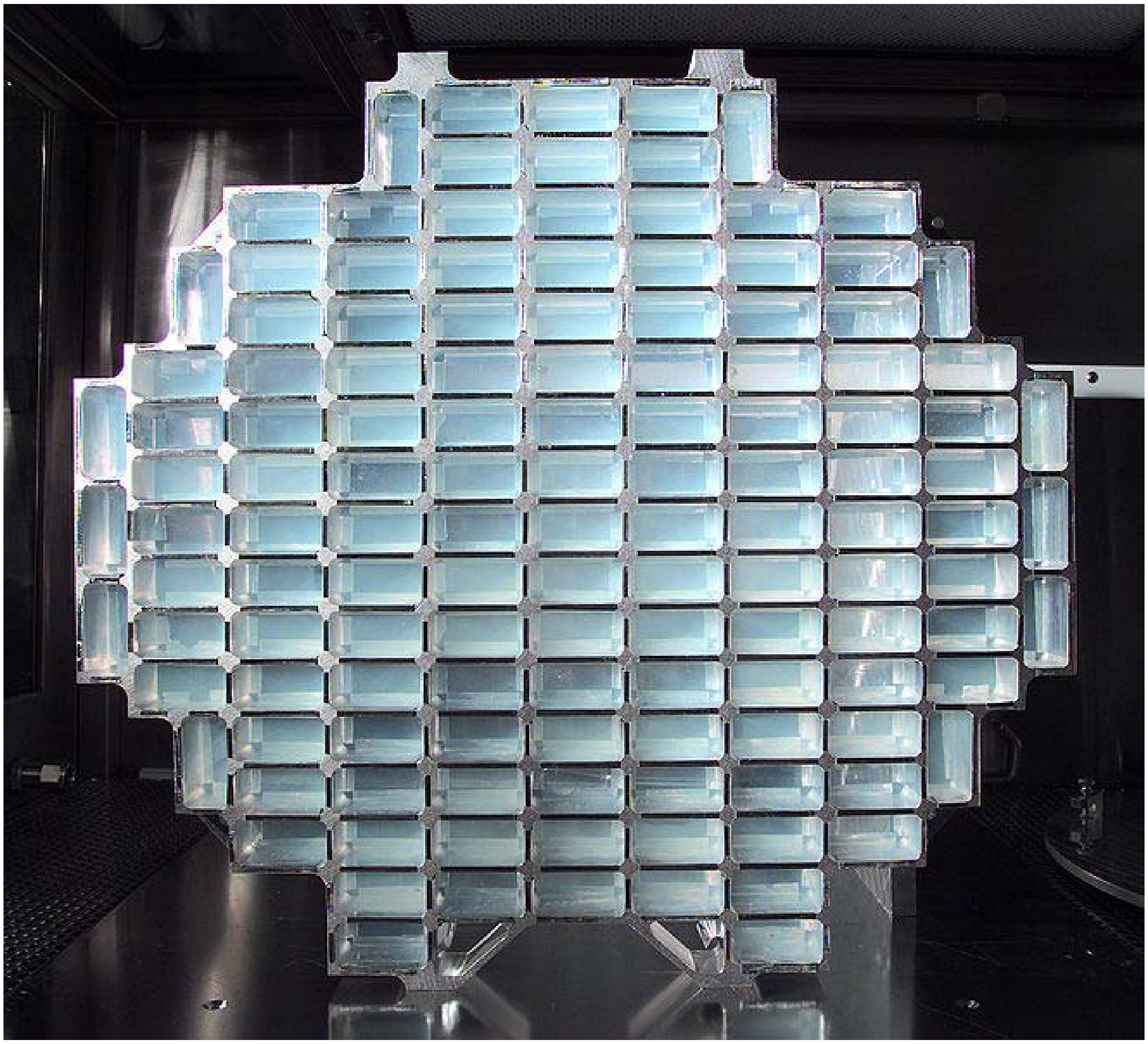
Being a sample return mission, Stardust is subject to the maximum contamination restrictions, classified under level 5 planetary protection. However, the risk of interplanetary contamination by alien life was judged low, for instance particle impacts at over 1000 miles per hour — even into aerogel — would destroy any known microorganism.

The total weight of the spacecraft, including the hydrazine propellant needed for deep space maneuvers, is 380 kilograms. The overall length of the main bus is 1.7 meters, about the size of a refrigerator or an average office desk. It appears orange-brown due to the blankets of Kapton film.

At one end of the spacecraft is the sample return capsule; the capsule contains the aerogel tray, and an arm to extend the tray. The opposite end of the spacecraft has the main dust shield, and the interface to the launch vehicle. Two sides of the spacecraft body hold solar arrays. Unlike most other missions, the silicon arrays do not articulate to track the sun after their initial deployment. The spacecraft is fairly passive and generates adequate power during the lengthy cruise portions of the mission. The encounter phase, when Stardust must orient the collector and dust shields at Wild 2 regardless of solar illumination, is relatively brief. Each array also has a dust shield. The remaining sides of the spacecraft contain the communications dish and scientific instruments.

Stardust runs VxWorks, an embedded operating system developed by Wind River Systems, on a RAD6000 32-bit processor. There are 128 megabytes for both program space and data collection.

Science payload

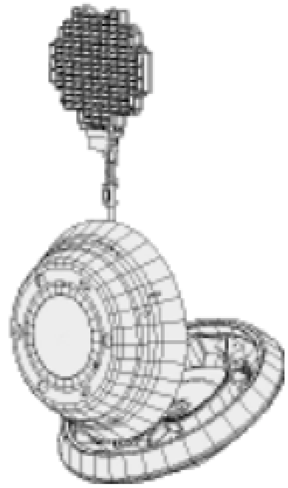


Dust Collector with aerogel blocks (NASA)

Aerogel sample collectors

Comet and interstellar particles are collected in ultra low density aerogel. More than 1,000 square centimeters of collection area is provided for each type of particle (cometary and interstellar). The collector tray contains ninety blocks of aerogel in a metal grid. The appearance of the grid has been likened to an ice cube tray; the round collector is about the size of a tennis racket.

When the spacecraft flew past the comet, the impact velocity of the particles in the coma as they were captured was 6100 metres per second, up to nine times the speed of a bullet fired from a rifle. Although the captured particles were each smaller than a grain of sand, high-speed capture could have altered their shape and chemical composition — or vaporized them entirely.



Stardust capsule with aerogel collector deployed

To collect the particles without damaging them, a silicon-based solid with a porous, sponge-like structure is used in which 99.8 percent of the volume is empty space. Aerogel is 1,000 times less dense than glass, another silicon-based solid. When a particle hits the aerogel, it buries itself in the material, creating a carrot-shaped track up to 200 times its own length, as it slows down and comes to a stop — like an airplane setting down on a runway and braking to reduce its speed gradually. Since aerogel is mostly transparent — a property earning it the nicknames "solid smoke", "frozen smoke" or "blue smoke" — scientists will use these tracks to find the tiny particles.

The aerogel was packed in a Sample Return Capsule (SRC) which was released from the spacecraft just before reentry, for a separate landing on a parachute, while the rest of the spacecraft fired its engines, putting it into orbit around the sun.

While there was some concern about this landing, as the capsule shares a parachute design with Genesis, a solar probe whose parachute did not deploy properly in 2004 due to an assembly and integration error, the Utah landing saw the spacecraft arrive intact and within a minute of estimates.

To analyse the aerogel for interstellar dust, about one million photographs will be taken, each one of a very small section of the gel. These will be distributed to home computer users who will be credited for any particles found, in a program called Stardust@home modeled after SETI@home and Mars Clickworkers.

Comet and Interstellar Dust Analyzer (CIDA)

Comet and Interstellar Dust Analyzer (CIDA)

The CIDA instrument is a time-of-flight mass spectrometer that determines the composition of individual dust grains which collide with a silver impact plate.

The purpose of the Cometary and Interstellar Dust Analyzer (CIDA) instrument on Stardust is to intercept and perform real-time compositional analysis of dust as it is encountered by the spacecraft for transmission back to Earth.

The CIDA separates ions' masses by comparing differences in their flight times. The operating principle of the instrument is the following: when a dust particle hits the target of the instrument, ions are extracted from it by the electrostatic grid. Depending on the polarity of the target positive or negative ions can be extracted. The extracted ions move through the instrument, are reflected in the reflector, and detected in the detector. Heavier ions take more time to travel through the instrument than lighter ones, so the flight times of the ions are then used to calculate their masses.

The CIDA is the same instrument design that flew on Giotto and two Vega program spacecraft where it obtained unique data on the chemical composition of individual particulates in Halley's coma. It consists of an inlet, a target, an ion extractor, a time-of-flight (TOF) mass spectrometer (MS) and an ion detector.

The co-investigator in charge of the CIDA is Jochen Kissel of Max-Planck-Institut für extraterrestrische Physik in Garching bei München, Germany where the instrument was developed. Electronics hardware was built by von Hoerner & Sulger GmbH in Schwetzingen Germany. Software for the CIDA instrument is developed by The Finnish Meteorological Institute.

Navigation camera (NavCam)

The Navigation camera is used for targeting the flyby of the Wild 2 nucleus, but also provides high-resolution science images of the comet.

The Navigation Camera (NC), an engineering subsystem, was used to optically navigate the spacecraft upon approach to the comet. This allowed the spacecraft to achieve the proper flyby distance, near enough to the nucleus, to assure adequate dust collection. The camera also served as an imaging camera to collect scientific data. The data includes high-resolution color images of the comet's nucleus, on approach and on departure, and broadband images at various phase angles while nearby. These images were used to construct a 3-D map of the nucleus in order to better understand its origin, morphology, to search for mineralogical inhomogeneities on the nucleus, and potentially to supply information on the nucleus rotation state. The camera will provide images, taken through different filters, that gave information on the gas and dust coma during approach and departure phases of the mission. These images are providing information on gas composition, gas and dust dynamics, and jet phenomena (if they exist).

The camera peers out of a "periscope." An initial fold mirror looks past the dust shield, and keeps the body of the camera out of the path of damaging dust particles. A scan mirror then gives the camera some panning capability, independent of the spacecraft orientation. This dual-mirror design also provides robustness. Upon approach to the nucleus, both mirrors are used to navigate and take images. Then, when the spacecraft is retreating from Wild 2, the camera looks "backward" by turning the scan mirror, bypassing the fold mirror. If comet dust has etched the fold mirror on approach, the mission can still take images with the clean scan mirror. Etching from Wild 2 did not appear to be severe; the spacecraft can still image future objects with either method.

Early in the mission, contamination threatened the camera's performance. Volatile substances from elsewhere on the spacecraft escaped in the vacuum of space ("outgassing"), and some redeposited on the camera, resulting in cloudy images. Although this did not impact the primary mission goal (the aerogel collectors), it would reduce the science return from Wild 2. Electric heaters, used to maintain the camera at a moderate temperature, were overdriven to "boil" off the contamination. The majority of deposits were eliminated, and test images were deemed acceptable. A similar problem appeared on the Cassini mission, with similar techniques and results.

Dust shield and monitors

Whipple shield

The Whipple shield is designed to protect the spacecraft during its flyby of comet Wild 2. It consists of three sections, two protecting the solar panels and one protecting the main spacecraft body. The first layer is made of composite panels. The panels are augmented by blankets of Nextel ceramic cloth. The shield is designed to protect Stardust from particles as large as 1 cm in diameter.

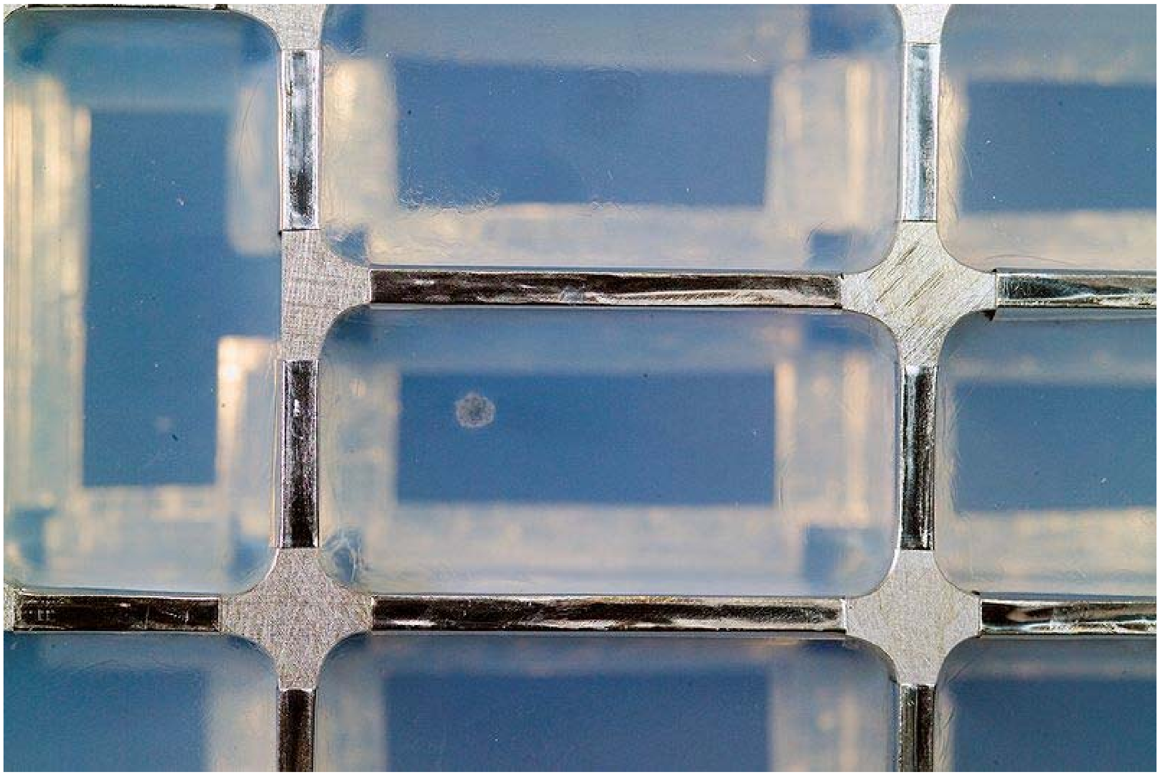
Dust Flux Monitors (DFM)

The DFM instrument, mounted on the front of the Whipple shield, monitors the flux and size distribution of particles in the environment.

Developed under the direction of Tony Tuzzalino at the University of Chicago, the DFMI is a highly sensitive instrument designed to detect particles as small as a few micrometres. It is based on a very special polarized plastic (PVDF) that generates electrical pulses when impacted or penetrated by small high speed particles.

The Dust Flux Monitor Instrument (DFMI) consists of a Sensor Unit (SU), Electronics Box (EB), and the two acoustic sensors mounted to the Stardust spacecraft. The SU is mounted to the Whipple shield, and the EB is mounted internally to the spacecraft enclosure.

Sample processing



Dust impact in Stardust collector

The samples returned by the spacecraft were flown by military transport from Utah to Ellington Air Force Base in Houston, Texas, then transferred by road to the Johnson Space Center in Houston, Texas. NASA officials said "prudence" dictated that the materials be transferred in secrecy, though the agency said they had received no specific security threats. According to the Houston Chronicle, the sample container was taken to a clean room facility which has "a cleanliness factor 100 times that of a hospital operating room to ensure the star and comet dust is not contaminated by earthly grime." Johnson Space Center is also the home of most of the moon rock samples brought back by the Apollo missions.

NASA made a preliminary estimation of a million microscopic specks of dust embedded in Stardust's aerogel collector. There are about 10 particles of 100 micrometers in size. The largest is around a millimeter. Johnson Space Center is the curator of the samples collected, as well as the interstellar dust particles, while as many as 150 scientists worldwide are analyzing those samples.

There is also an estimated 45 interstellar dust impacts on the Stardust Interstellar Dust Collector (SIDC), which resides on the flip side of the cometary dust collector. The search for these grains is being done by a volunteer team through the distributed computing project called Stardust@Home.

Sample analysis

Seven papers in *Science* magazine (December 2006) discuss details of the sample analysis. Among their findings are discoveries of a wide range of organic compounds, including two that contain biologically usable nitrogen. Indigenous aliphatic hydrocarbons were found with longer chain lengths than those observed in the diffuse interstellar medium. The Stardust samples contain abundant amorphous silicates in addition to crystalline silicates such as olivine and pyroxene. The presence of crystalline silicates in Wild 2 is consistent with mixing of solar system and interstellar matter, something which had been deduced spectroscopically from previous astronomical observations. No hydrous silicates or carbonate minerals were detected, which suggests a lack of aqueous processing of Wild 2 dust. Very few pure carbon (CHON) particles were found in the samples returned. However, the organic compounds methylamine and ethylamine derived from the comet were found in aerogel not associated with specific particles.

In 2010 Dr Andrew Westphal announced that Stardust@home volunteer Bruce Hudson found a track (labeled "I1043,1,30") among the many images of the aerogel which may contain an interstellar dust grain. Hudson was allowed to choose a name for the dust grain, and called it *Orion*.