

A photograph of the International Space Station (ISS) in orbit above Earth. The station's complex structure, including the large solar panel arrays, is clearly visible against the blue and white clouds of the planet. The perspective is from a high angle, looking down at the station as it orbits.

Handbook of
Space and Solar System
Exploration in 2000s

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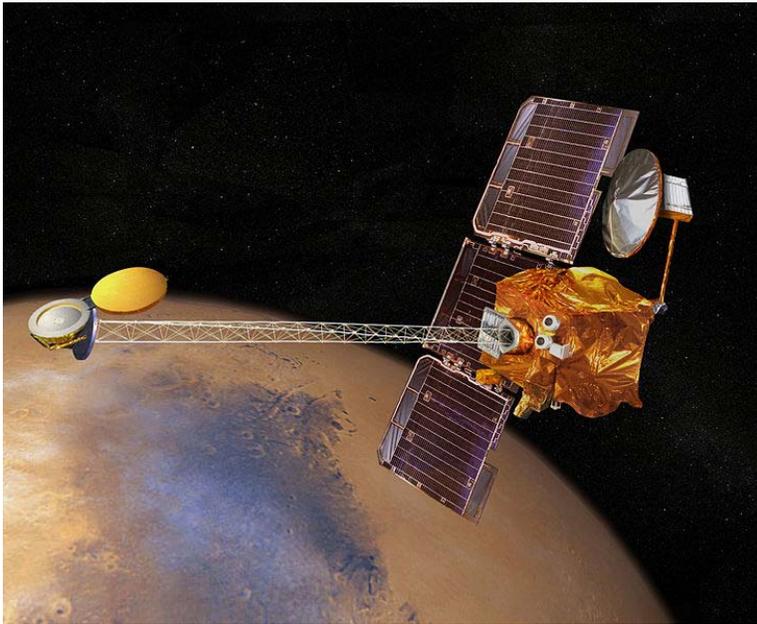
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Chapter- 1

Space and Solar System Exploration in 2001

2001 Mars Odyssey

2001 Mars Odyssey



Conceptual drawing of *2001 Mars Odyssey* over Mars.

Operator	NASA
Mission type	Orbiter
Satellite of	Mars
Orbital insertion date	2001-10-24 02:18:00 UTC
Launch date	2001-04-07 15:02:22 UTC (9 years, 9 months, and 9 days ago)
Launch vehicle	Delta II 7425

Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
	In progress (Extended Mission)
Mission duration	(8 years, 11 months, and 17 days elapsed)
	Primary mission (completed 2004-08-24)
COSPAR ID	2001-014A
Mass	376 kg (829 lb)
Power	750 W (Photovoltaic array/NiHM Battery)
	Orbital elements
Semimajor axis	3785 km (~400 km above surface)
Eccentricity	0.0115
Inclination	93.2 deg
Orbital period	1.964 hours

2001 Mars Odyssey is a robotic spacecraft orbiting the planet Mars. The project was developed by NASA, and contracted out to Lockheed Martin, with an expected cost for the entire mission of US\$297 million. Its mission is to use spectrometers and electronic imagers to hunt for evidence of past or present water and volcanic activity on Mars. It is hoped that the data Odyssey obtains will help answer the question of whether life has ever existed on Mars. It also acts as a relay for communications between the Mars Exploration Rovers and the Phoenix lander to Earth. The mission was named after the movie *2001: A Space Odyssey*.

Odyssey was launched April 7, 2001 on a Delta II rocket from Cape Canaveral Air Force Station, and reached Mars orbit on October 24, 2001, at 2:30 a.m. UTC (October 23, 7:30 p.m. PDT, 10:30 p.m. EDT). The spacecraft's main engine fired in order to brake the spacecraft's speed, which allowed it to be captured into orbit around Mars. Odyssey used a technique called "aerobraking" that gradually brought the spacecraft closer to Mars with each orbit. By using the atmosphere of Mars to slow down the spacecraft in its orbit, rather than firing its engine or thrusters, Odyssey was able to save more than 200 kilograms (440 lb) of propellant. Aerobraking ended in January, and Odyssey began its science mapping mission on February 19, 2002.

Naming

Mars Odyssey was originally a component of the *Mars Surveyor 2001* program, and was named the **Mars Surveyor 2001 Orbiter**. It was intended to have a companion spacecraft known as Mars Surveyor 2001 Lander, but the lander mission was canceled in May 2000 following the failures of Mars Climate Orbiter and Mars Polar Lander in late 1999. Subsequently, the name *2001 Mars Odyssey* was selected for the orbiter as a specific tribute to the vision of space exploration shown in works by Arthur C. Clarke, including *2001: A Space Odyssey*. The music from *Mythodea* by Greek composer Vangelis was used as the theme music for the mission.

Scientific instruments

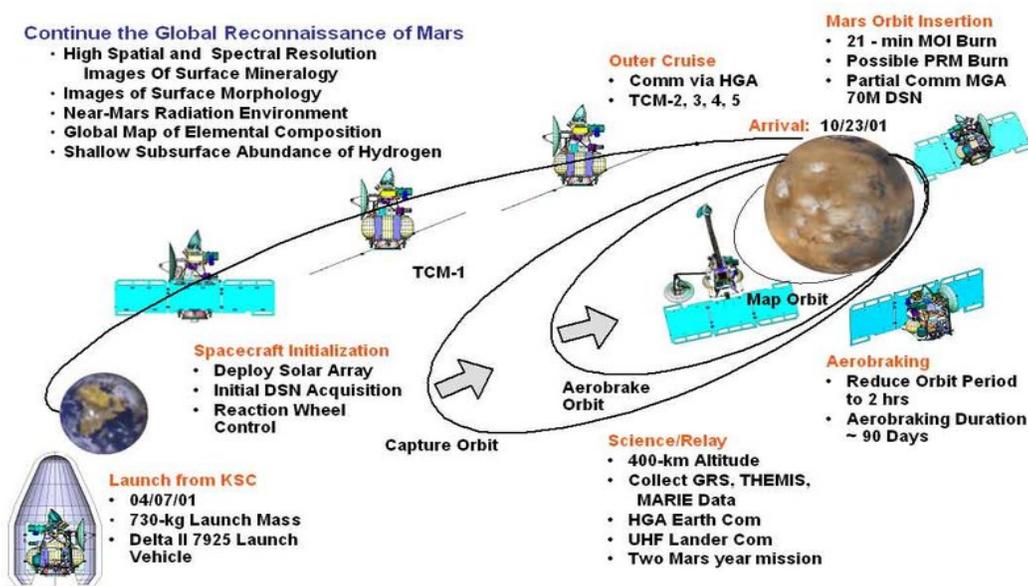
The three primary instruments Odyssey uses are the:

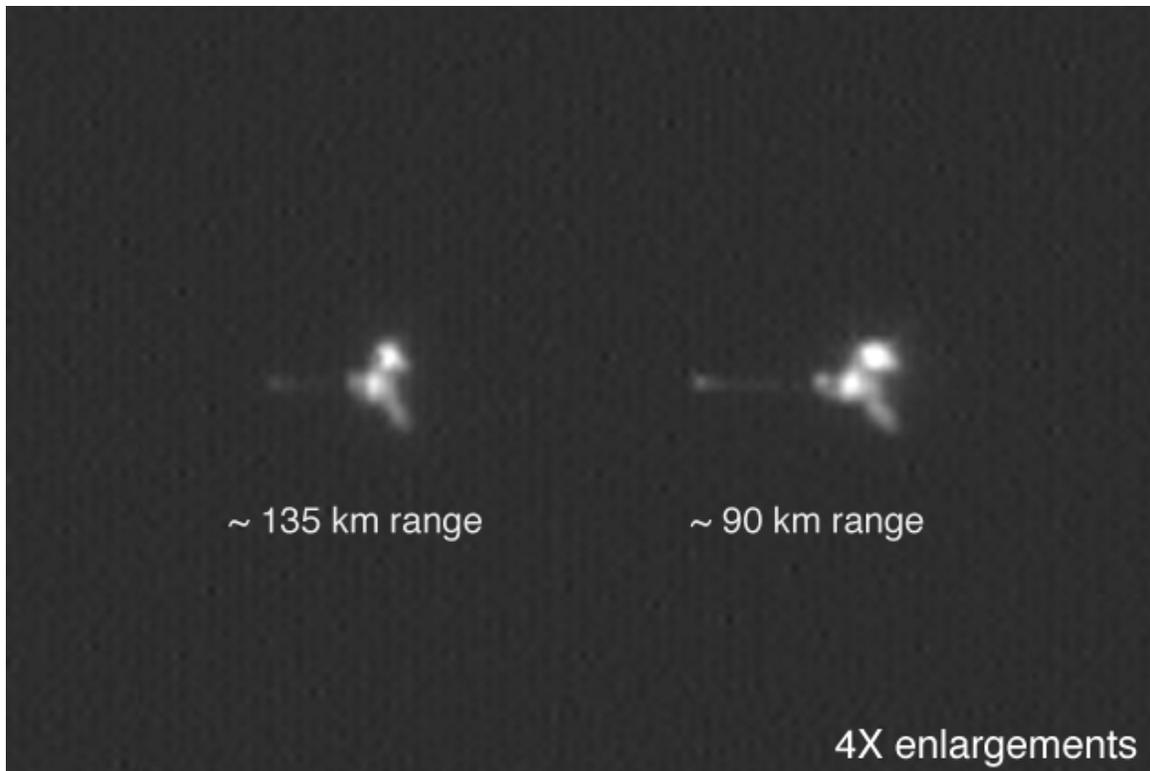
- **Thermal Emission Imaging System (THEMIS).**
- **Gamma Ray Spectrometer (GRS)**, which includes the **High Energy Neutron Detector (HEND)**, provided by Russia.
- **Mars Radiation Environment Experiment (MARIE).**

On May 28, 2002, NASA reported that Odyssey's GRS had detected large amounts of hydrogen, a sign that there must be ice lying within a meter of the planet's surface.

Mission

2001 Mars Odyssey Mission





Summary of the Mars Odyssey mission

Mars Odyssey as imaged by Mars Global Surveyor

NASA has approved a third two year extended mission, through September 2010, to allow for the observation of year-to-year differences in phenomena like polar ice, clouds, and dust storms, as well as a much more sensitive mapping of martian minerals. On September 30, 2008 the spacecraft activated its thrusters for 6 minutes, in order to begin altering its orbit, to gain an even better sensitivity for its infrared mapping of Martian minerals. The change will cause the spacecraft to move from a late afternoon orbit to a mid afternoon orbit by decreasing the time it passes over a location by 20 seconds per day, until a new thruster burn occurs in late 2009 which will stabilize its orbit.

Unfortunately, the new orbit will eliminate the use of the Gamma Ray Spectrometer Suite, due to potential for overheating the instrument at the new orbit. The extension will also continue Odyssey's support for other Mars missions. The orbiter contains enough propellant to operate at least until 2015. About 85 percent of images and other data from NASA's twin Mars Exploration Rovers, Spirit and Opportunity, have reached Earth via communications relay by Odyssey, which receives transmissions from both rovers every day. The orbiter helped analyze potential landing sites for the rovers and performed the same task for NASA's Phoenix mission, which landed on Mars in May, 2008. Odyssey aided NASA's Mars Reconnaissance Orbiter, which reached Mars in March 2006, by monitoring atmospheric conditions during months when the newly arrived orbiter used aerobraking to alter its orbit into the desired shape.

Water on Mars

On July 31, 2008, NASA announced that the Phoenix lander confirmed the presence of water on Mars, as predicted in 2002 based on data from the Odyssey orbiter. The science team is trying to determine whether the water ice ever thaws enough to be available for biology, and if carbon-containing chemicals and other raw materials for life are present.

Genesis

Genesis



In its collecting configuration, the Genesis spacecraft exposed several types of solar wind collectors as well as solar wind ion and electron monitors.

Operator	NASA / JPL
Major contractors	Lockheed Martin Space Systems
Mission type	Sample return
Satellite of	Earth L ₁ , Sun
Orbital insertion date	2001-11-16

Launch date	2001-08-08, 16:13:40 UTC (9 years, 5 months, and 7 days ago)
Launch vehicle	Delta II 7326
Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
Mission duration	December 3, 2001 - April 22, 2004 (2 years, 5 months, and 19 days) (currently in sleep mode) Sample return <i>(completed 2004-09-08)</i>
Landing site	Dugway Proving Ground <i>(crashed)</i>
COSPAR ID	2001-034A
Mass	494 kg (1,089 lb)
Power	254.0 W (Solar array / Ni-H ₂ batter)

Instruments

Spectral band	GE-2, Trans. 9, C-band
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The **Genesis** spacecraft collected a sample of solar wind and returned it to Earth for analysis. It was the first NASA "sample return mission" to return material since the Apollo Program, and the first to return material from beyond the orbit of the Moon. It was launched on August 8, 2001, and crash-landed on September 8, 2004 after a design flaw prevented the deployment of its drogue parachute. The crash contaminated many of the sample collectors but, although most were damaged, a large fraction of the collectors were recovered. The science team demonstrated that some of the contamination could be removed, that some could be avoided, and that solar-wind could be analyzed using a variety of approaches. It is relatively easy to see the solar wind, but the precision measurements are difficult and techniques are still being refined in laboratories worldwide. Still, as of March 2008 there was reason to believe that all of the mission's major science objectives will be achieved successfully.

Objective



A Genesis collector array in the Genesis clean lab at the Johnson Space Center (photo courtesy NASA). Hexagons consist of a variety of ultra-pure, semiconductor-grade wafers, including silicon, commercial “sapphire” (i.e. corundum), gold on sapphire, diamond-like carbon films, and other materials.

The Mission’s primary science objectives as paraphrased from the original proposal fact sheet:

- Obtain precise solar isotopic abundances of ions in the solar wind, as essentially no data having a precision sufficient for solving planetary science problems are available.
- Obtain greatly improved solar elemental abundances by factor of 3-10 in accuracy over what is in the literature.
- Provide a reservoir of solar matter for 21st century science to be archived in the manner as the lunar samples.

Notice that the Genesis mission science objectives refer back to the composition of the sun, not that of the solar wind. Scientists want a sample of our sun because a preponderance of evidence suggests that the outer layer of the sun preserves the composition of our early solar nebula. Therefore, knowing the exact elemental and isotopic composition of the outer layer of our sun is effectively the same as knowing the

elemental and isotopic composition of our nebula. We could then use that data to model how planets and other solar-system objects formed and then extend those results to understanding stellar evolution and the formation of solar systems elsewhere in the universe.

Clearly the ideal scientific option would be to send a spacecraft to the sun and grab some solar plasma; however, obtaining solar matter is not that straightforward because of the intense heat (millions of degrees kelvin) of the Sun's superheated gases as well as the dynamic electromagnetic environment of the corona, whose flares regularly interfere with the electronics of distant spacecraft. Luckily, the sun continuously sheds bits of its outer layer in the form of solar wind. Even better luck, data (prior to Genesis) suggests that the rock-forming elements are thought to maintain their relative proportions throughout the process of solar wind formation.

Accordingly, in order to practically meet the mission science objectives, the Genesis spacecraft was designed to collect solar wind ions and bring them back to Earth for analysis. Genesis carried a number of different solar-wind collectors, all of which passively collected solar wind; that is, the collectors sat in space facing the sun, while the ions in the solar-wind crashed into them at speeds over 200 km/sec and, on impact, buried themselves in the surface of the collectors. This passive collection is a process similar to that used by the semi-conductor industry to make certain types of devices, and a simulation of the process is given by the free-access program SRIM.

Most of the Genesis collectors continuously sampled all of the solar wind the spacecraft encountered (aka 'bulk solar wind'). However, the spacecraft also carried three arrays of collectors which were deployed when specific "regimes" (fast, slow, coronal mass ejections) of solar wind were encountered, as determined by the electron- and ion-monitors on board. These deployable collector arrays were designed to provide data to test the hypothesis that the rock-forming elements keep their relative proportions throughout the processes forming solar wind.

There was a third, very important type of collector on Genesis: the concentrator. The concentrator collected bulk solar wind, but was discriminating in that it electrostatically repelled hydrogen and had enough voltage that it focused the light solar wind elements (e.g., C, O, N, S) onto a small target, concentrating those ions by a factor of ~20. This concentrator was the electrostatic equivalent of using a parabolic mirror from a telescope to cook a hot dog, and somewhat like using a magnifying glass to start a fire. The objective of the concentrator was to bring back a sample with enhanced amounts of solar wind ions to make it possible for analysts to precisely measure the isotopes of the light elements.

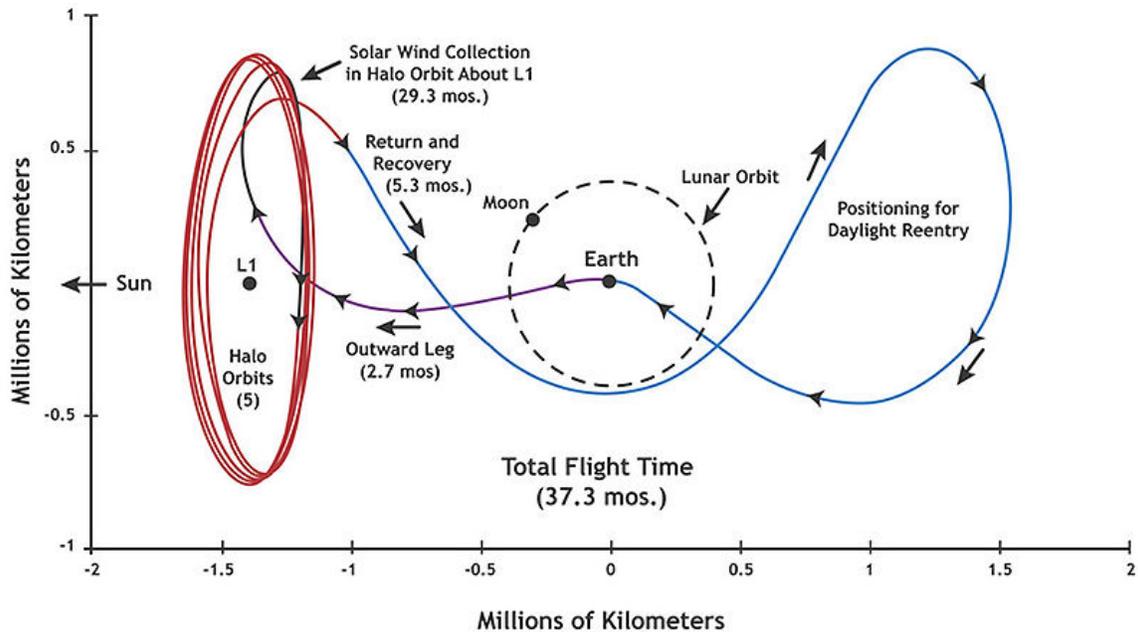
Operation

Mission profile



The launch of Genesis

Genesis was a Discovery-class mission of the NASA Jet Propulsion Laboratory (JPL) at the California Institute of Technology (Caltech). The spacecraft was designed and built by Lockheed Martin Space Systems at a total mission cost of US\$264 million.



Genesis mission trajectory and flight plan

NASA launched the craft on a Delta II 7326 rocket on August 8, 2001 at 16:13:40 UTC from Cape Canaveral. Following launch, Genesis cruised to the Earth L_1 then performed a Lissajous orbit insertion maneuver, entering an elliptical orbit about L_1 on November 16, 2001. Genesis exposed its collector arrays to pick up solar wind particles expelled from the Sun on December 3, 2001. The collection process ended after 850 days, on April 1, 2004, with the spacecraft completing five halo loops around L_1 . Genesis began its return to Earth on April 22, 2004. The return phase included an orbital detour toward the Earth L_2 so that the craft could be recovered during the daytime, as a direct approach precluded this possibility. After completing one halo loop about L_2 , then returned to Earth for a planned September 8, 2004 recovery.

Recovery phase (planned)



The planned mid-air retrieval was extensively rehearsed

Following completion of the collection phase, the collector arrays were stowed in a sample return capsule, and the spacecraft returned to Earth. As the capsule was approaching Earth and at the first stages of re-entry, all appeared well.

A normal parachute landing might have damaged the delicate samples, so the mission design called for a mid-air retrieval of the sample return capsule. About 33 km above the ground, a drogue parachute was planned to be deployed to slow descent. Then, at a height of 6.7 km, a large parafoil was to be deployed to slow descent further and leave the capsule in stable flight. A helicopter, with a second helicopter as a backup, was then to

attempt to catch the capsule by its parachute on the end of a 5 meter hook. Once retrieved, the capsule would have been soft-landed.

Recovery phase (actual)



The Genesis capsule tumbles to Earth moments before it crashes

The sample return capsule entered Earth's atmosphere at 16:55 UTC September 8, 2004 over northern Oregon with a velocity of approximately 11.04 km/s (24,706 mph). Due to a design flaw in a deceleration sensor, parachute deployment was never triggered, and the spacecraft descended slowed only by its own air resistance. The planned mid-air retrieval could not be carried out. The spacecraft crashed into the desert floor of the Dugway Proving Ground in Tooele County, Utah at about 86 metres per second (311 km/h (193 mph)).

The capsule broke open on impact, and part of the inner sample capsule was also breached. The damage was less severe than might have been expected given its velocity; it was to some extent cushioned by falling into fairly soft muddy ground.

Sample extraction & results



The sample return capsule crashed into the Utah desert floor, breaking open the capsule. The capsule is about 1.5 m (4.9 ft) in diameter and has a mass of 275 kg (600 lb)

Unfired pyrotechnic devices in the parachute deployment system and toxic gases from the batteries delayed the recovery team's approach to the crash site. Once all was made safe, the damaged sample-return capsule was secured and moved to a clean room for inspection; simultaneously a crew of trained personnel scoured the site for collector fragments and sampled the local desert soil to archive as a reference by which to identify possible contaminants in the future. Recovery efforts by Genesis team members at the Utah Test and Training range – which included inspecting, cataloging and packaging various collectors—took four weeks.

Initial investigations showed that some wafers had crumbled to dust on impact, but others were largely intact. Desert dirt entered the capsule, but not liquid water. Because the solar wind particles are expected to be embedded in the wafers, whereas the contaminating dirt is likely just to lie on the surface, it may be possible to separate the dirt from the samples.

The analysis team was hopeful of being able to extract some useful data from the capsule. Roger Wiens, of the Los Alamos National Laboratory stated on September 10, 2004 that because much of the inner canister was still intact, and despite serious contamination, "We should be able to meet many, if not all, of our primary science goals". On September 21, 2004 the extraction was said to be going well, with wafer fragments beginning to be

extracted from the science canister. NASA announced on January 27, 2005, that a first sample piece of an aluminum wafer was sent to scientists at Washington University in St. Louis for analysis.

On April 20, 2005, NASA announced that scientists at the Johnson Space Center in Houston had removed the four solar-wind collectors from an instrument called the concentrator and found them in excellent shape. The concentrator's targets collected solar-oxygen ions during the mission and will be analyzed to measure solar-oxygen isotopic composition, the highest-priority measurement objective for Genesis.

Confirming the integrity of the wafers and the recovery process, on October 18, 2007, the scientists at Washington University in St. Louis published detailed neon and argon isotope fractionation findings. Argon and neon isotopes in samples of three types of solar wind (fast, slow, and coronal mass ejections from the Sun's surface) were captured and quantified. The findings effectively discount some theoretical models of stellar genesis. This much more precise data complements knowledge gained from earlier lunar argon measurements.

It was announced by Kevin McKeegan on March 10, 2008 that analysis of a silicon wafer has shown that the Sun has a higher proportion of oxygen-16 than does the Earth. The measurement was made after the upper 20 nm of the wafer was removed with a beam of cesium ions. This implies that an unknown process depleted oxygen-16 from the Sun's disk of protoplanetary material prior to the coalescence of dust grains that formed the Earth.

Ironically, it was not terrestrial desert soil introduced in the crash that proved most difficult to deal with during the sample analysis process but the craft's own flight-introduced compounds such as lubricants and craft-building materials.

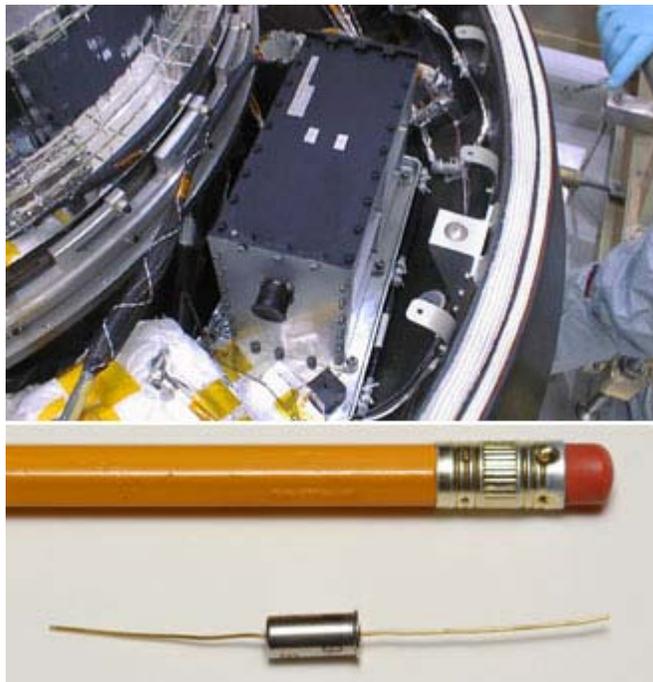
Fate of spacecraft bus

After releasing the sample return capsule on September 8, 2004, the spacecraft bus quickly headed back toward the vicinity of the Earth-Sun Lagrange Point (L1). A trajectory correction maneuver was performed on November 6, 2004 to allow it eventually to leave L1 if the bus was not used for an extended mission. Final commands were radiated on December 2, 2004, to put Genesis into hibernation. While in this "safe" mode, it will continue transmitting health and safety information, autonomously pointing its solar arrays toward the Sun. The spacecraft bus left L1 around February 1, 2005, staying in a heliocentric orbit leading the Earth.

Mishap Investigation Board (MIB)



Genesis staff have started sorting through the debris from the sample canister



Closeup of the type of accelerometer that was installed backwards, alongside a pencil for scale (lower section) with a view of the spacecraft capsule and bus.

A 16-member NASA Genesis Mishap Investigation Board (MIB) was quickly formed, including experts on pyrotechnics, avionics, and other relevant specialties. The MIB started its work on September 10, 2004, when it arrived at Dugway Proving Ground. It determined that all scientific hardware meant to be curated by the Johnson Space Center could be released and were not needed for the work of the board. Both JPL and Lockheed Martin began to prepare flight data and other records for the MIB.

It was announced on September 23, 2004, that the capsule, having had the science material extracted, would be moved to the Lockheed Martin Space Systems facility near Denver, Colorado, for MIB use.

A first possible root cause of the failed deployment of the parachutes was announced in an October 14 press release. Lockheed Martin had built the system with an acceleration sensor's internal mechanisms wrongly oriented, and design reviews had not caught the mistake. The intended design was to make an electrical contact inside the sensor at 3 g (29 m/s²), maintaining it through the maximum expected 30 g (290 m/s²), and breaking the contact again at 3 g to start the parachute release sequence. Instead, no contact was ever made.

The same general parachute concept was also used on the Stardust comet sample return spacecraft, which landed successfully in 2006; but that system was said not to have Genesis's flaw.

NASA investigation board chair Michael Ryschkewitsch noted that none of the stringent review procedures at NASA had picked up a mistake: "It would be very easy to mix this up."

This mishap is strikingly similar to the original event that inspired Edward A. Murphy, Jr. to formulate the now-famous Murphy's Law: an accelerometer installed backwards. On January 6, 2006, Ryschkewitsch revealed that a pre-test procedure on the craft was skipped by Lockheed Martin, and added that the test could have easily detected the problem.

Chapter- 2

Space and Solar System Exploration in 2002

CONTOUR



CONTOUR launch preparations

The *COMet Nucleus TOUR* (CONTOUR) was a NASA Discovery-class space probe that failed shortly after its July 2002 launch. It had as its primary objective close flybys of two comet nuclei with the possibility of a flyby of a third known comet or an as-yet-undiscovered comet.

The two comets scheduled to be visited were Encke and Schwassmann-Wachmann-3, and the third target was d'Arrest. It was hoped that a new comet would have been discovered that would have been in the inner solar system between 2006 and 2008, in which case the spacecraft trajectory would have been changed if possible to rendezvous with the new comet. Scientific objectives included imaging the nuclei at resolutions of 4 m, performing spectral mapping of the nuclei at resolutions of 100–200 m, and obtaining detailed compositional data on gas and dust in the near-nucleus environment, with the goal of improving our knowledge of the characteristics of comet nuclei.

After ignition on 15 August 2002 of the solid rocket motor intended to inject the spacecraft into solar orbit, contact with the probe could not be re-established. Ground-based telescopes later found three objects along the course of the satellite, leading to the speculation that it had been destroyed. Attempts to contact the probe were ended on 20 December 2002. The probe accomplished none of its primary scientific objectives, but did prove out some technologies such as the APL-developed non-coherent spacecraft navigation technique, which is now used on the New Horizons spacecraft.

Spacecraft design

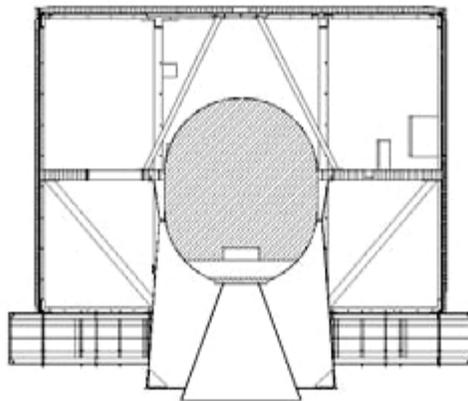


Diagram of CONTOUR, showing the internal solid rocket motor

The *CONTOUR* spacecraft had a total fueled mass of 775 kg, including 70 kg of hydrazine fuel and a Star 30BP booster with a mass of 377 kg. Power was provided by a body-mounted solar array designed for operation at distances between 0.75 and 1.5 AU from the Sun. It was three-axis stabilized for encounters and spin-stabilized during cruise mode between encounters.

CONTOUR's Command/Data-handling and Guidance/Control computers each used the Mongoose-V microprocessor. Communications were through a fixed 0.45 m diameter high-gain antenna to support data rates greater than 100 kbit/s at encounters. Data and images were stored on two 3.3 Gbit solid-state recorders with a capacity of 600 images.

The spacecraft was equipped with four primary science instruments, the Contour Remote Imager/Spectrograph (CRISP), the Contour Aft Imager (CAI), the Dust Analyzer (CIDA), and the Neutral Gas Ion Mass Spectrometer (NGIMS).

Mission

CONTOUR launched on a Delta 7425 (a Delta II Lite launch vehicle with four strap-on solid-rocket boosters and a Star 27 third stage) on July 3, 2002 at 6:47:41 UT (2:47:41 a.m. EDT) into a high-apogee Earth orbit with a period of 5.5 days from Cape Canaveral Air Force Station. Following a series of phasing orbits, the Star 30 solid rocket motor was used to perform an injection maneuver on August 15, 2002 to put CONTOUR in the proper trajectory for an Earth flyby in August 2003 followed by an encounter with comet Encke on 12 November 2003 at a distance of 100 to 160 km and a flyby speed of 28.2 km/s, 1.07 AU from the Sun and 0.27 AU from Earth. During the maneuver the probe was lost.

Three more Earth flybys would have followed, in August 2004, February 2005, and February 2006. On 18 June 2006 CONTOUR would have encountered comet Schwassmann-Wachmann-3 at 14 km/s, 0.95 AU from the Sun and 0.33 AU from Earth. Two more Earth flybys were scheduled in February 2007 and 2008, and a flyby of comet d'Arrest might have occurred on 16 August 2008 at a relative velocity of 11.8 km/s, 1.35 AU from the Sun and 0.36 AU from Earth. All flybys would have had a closest encounter distance of about 100 km and would have occurred near the period of maximum activity for each comet. After the comet Encke encounter, CONTOUR might have been retargeted towards a new comet if one was discovered with the desired characteristics (e.g. active, brighter than absolute magnitude 10, perihelion within 1.5 AU).

Investigation into failure

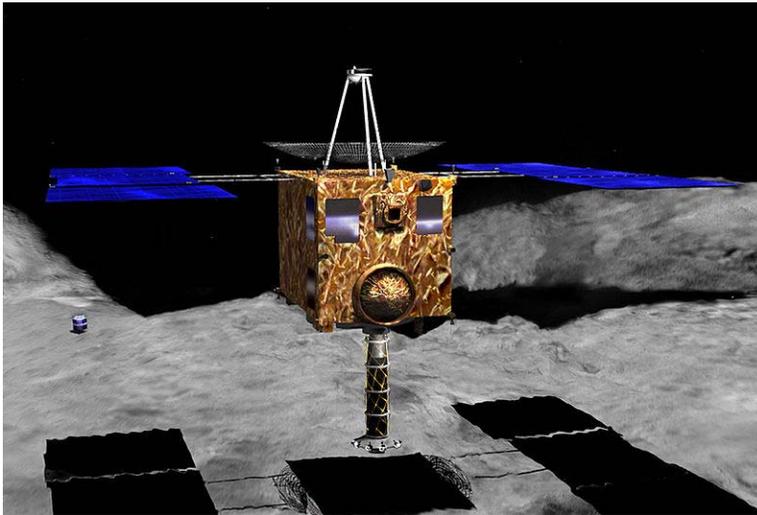
According to NASA: "An investigation board concluded that the most likely cause of the mishap was structural failure of the spacecraft due to plume heating during the solid-rocket motor burn. Alternate possible but less likely causes determined were catastrophic failure of the solid rocket motor, collision with space debris, and loss of dynamic control of the spacecraft."

Chapter- 3

Space and Solar System Exploration in 2003

Hayabusa

Hayabusa



A computer rendering of Hayabusa above Itokawa's surface

Operator	● JAXA
Mission type	Asteroid sample return
Current destination	Returned to Earth on 13 June 2010
Launch date	9 May 2003
Launch vehicle	● M-V
Mission duration	7 years, 1 month and 4 days
COSPAR ID	2003-019A
Mass	510 kg (dry 380 kg)

Instruments

AMICA, LIDAR, NIRS, XRS

Hayabusa (はやぶさ?, literally "peregrine falcon") was an unmanned spacecraft developed by the Japan Aerospace Exploration Agency to return a sample of material from a small near-Earth asteroid named 25143 Itokawa to Earth for further analysis.

Hayabusa, formerly known as **MUSES-C** for Mu Space Engineering Spacecraft C, was launched on 9 May 2003 and rendezvoused with Itokawa in mid-September 2005. After arriving at Itokawa, Hayabusa studied the asteroid's shape, spin, topography, colour, composition, density, and history. In November 2005, it landed on the asteroid and collected samples in the form of tiny grains of asteroidal material, which were returned to Earth aboard the spacecraft on 13 June 2010.

The spacecraft also carried a detachable miniland, MINERVA, but this failed to reach the surface.

Mission firsts



Denis J. P. Moura (left) and Junichiro Kawaguchi (right) at the 2010 International Astronautical Congress (IAC)

Other spacecraft, notably Galileo and NEAR Shoemaker both sent by NASA, have visited asteroids before, but the Hayabusa mission was the first time that an attempt was made to return an asteroid sample to Earth for analysis.

In addition, Hayabusa was the first spacecraft designed to deliberately land on an asteroid and then take off again (*NEAR Shoemaker* made a controlled descent to the surface of 433 Eros in 2000, but it was not designed as a lander and was eventually deactivated after it arrived). Technically, Hayabusa was not designed to "land"; it simply touches the surface with its sample capturing device and then moves away. However, it was the first craft designed from the outset to make contact with the surface of an asteroid. Junichiro Kawaguchi of the Institute of Space and Astronautical Science was appointed to the leader of the mission.

Despite its designer's intention of a momentary contact, Hayabusa did land and sit on the asteroid surface for about 30 minutes.

Mission profile



The half-scale model of Hayabusa at the IAC in 2010

The Hayabusa spacecraft was launched on 9 May 2003 at 04:29:25 UTC on an M-V rocket from the Uchinoura Space Center (still called Kagoshima Space Center at that time). Following launch, the spacecraft's name was changed from the original MUSES-C to Hayabusa, the Japanese word for falcon. The spacecraft's xenon ion engines (four separate units), operating near-continuously for two years, slowly moved Hayabusa toward a September 2005 rendezvous with Itokawa. As it arrived, the spacecraft did not go into orbit around the asteroid, but remained in a station-keeping heliocentric orbit close by.

Hayabusa surveyed the asteroid surface from a distance of about 20 km, the "gate position". After this the spacecraft moved closer to the surface (the "home position"), and then approached the asteroid for a series of soft landings and for the collection of samples at a safe site. Autonomous optical navigation was employed extensively during this period because the long communication delay prohibits Earth-based real-time commanding. At the second Hayabusa touchdown with its deployable collection horn, the spacecraft was programmed to fire tiny projectiles at the surface and then collect the resulting spray. Some tiny specks were collected by the spacecraft for analysis back on Earth.

After a few months in proximity to the asteroid, the spacecraft was scheduled to fire its engines to begin its cruise back to Earth. This maneuver was delayed due to problems with attitude control and the thrusters of the craft. Once it was on its return trajectory, the re-entry capsule was released from the main spacecraft three hours before reentry, and the capsule coasted on a ballistic trajectory, re-entering the Earth's atmosphere at 13:51, 13 June 2010 UTC. It is estimated that the capsule experienced peak deceleration of about 25 G and heating rates approximately 30 times those experienced by the Apollo spacecraft. It landed via parachute near Woomera, Australia.

In relation to the mission profile, JAXA defined the following success criteria and corresponding scores for major milestones in the mission prior to the launch of the Hayabusa spacecraft. As it shows, the Hayabusa spacecraft is a platform for testing new technology and the primary objective of the Hayabusa project is the world's first implementation of microwave discharge ion engines. Hence 'operation of ion engines for more than 1000 hours' is an achievement that gives a full score of 100 points, and the rest of the milestones are a series of world's first-time experiments built on it.

Success Criteria for HAYABUSA	Points	Status
Operation of Ion Engines	50 points	Success
Operation of Ion Engines for more than 1000 hours	100 points	Success
Earth Gravity Assist with Ion Engines	150 points	Success
Rendezvous with Itokawa with Autonomous Navigation	200 points	Success
Scientific Observation of Itokawa	250 points	Success
Touch-down and Sample Collection	275 points	Success
Capsule Recovered	400 points	Success

MINERVA mini-lander

Hayabusa carried a tiny mini-lander (weighing only 591 g, and approximately 10 cm tall by 12 cm in diameter) named "MINERVA" (short for MIcro/Nano Experimental Robot Vehicle for Asteroid). Unfortunately, an error during deployment resulted in the craft's failure.

This solar-powered vehicle was designed to take advantage of Itokawa's very low gravity by using an internal flywheel assembly to hop across the surface of the asteroid, relaying images from its cameras to Hayabusa whenever the two spacecraft were in sight of one another.

MINERVA was deployed on 12 November 2005. The lander release command was sent from Earth, but before the command could arrive, Hayabusa's altimeter measured its distance from Itokawa to be 44 m and thus started an automatic altitude keeping sequence. As a result, when the MINERVA release command arrived, MINERVA was released while the probe was ascending and at a higher altitude than intended, so that it escaped Itokawa's gravitational pull and tumbled into space.

Had it been successful, MINERVA would have been the first space hopper to see action. Instead it joins ranks with the hopper carried on the failed Phobos 2 mission, which also never saw use.

Scientific and engineering importance of the mission

Scientists' current understanding of asteroids depends greatly on meteorite samples, but it is very difficult to match up meteorite samples with the exact asteroids from which they came. Hayabusa would solve this problem by bringing back pristine samples from a specific, well-characterized asteroid. Accordingly, Hayabusa "will bridge the gap between ground observation data of asteroids and laboratory analysis of meteorite and cosmic dust collections," says mission scientist Hajime Yano. Also in comparing the data from the onboard instruments of the Hayabusa with the data from the NEAR Shoemaker mission will put the knowledge on a wider level.

The Hayabusa mission has a very deep engineering importance for JAXA, too. It allows JAXA to further test its technologies in the fields of ion engines, autonomous and optical navigation, deep space communication, and close movement on objects with low gravity among others. Second, since it was the first-ever preplanned soft contact with the surface of an asteroid (the NEAR Shoemaker landing on 433 Eros was not preplanned) it has enormous influence on further asteroid missions.

Changes in mission plan

The Hayabusa mission profile has been modified several times, both before and after launch.

- The spacecraft was originally intended to launch in July 2002 to the asteroid 4660 Nereus (the asteroid (10302) 1989 ML was considered as an alternative target). However, a July 2000 failure of Japan's M-5 rocket forced a delay in the launch, putting both Nereus and 1989 ML out of reach. As a result, the target asteroid was changed to 1998 SF₃₆, which was soon thereafter named for Japanese rocket pioneer Hideo Itokawa.
- Hayabusa was to deploy a small rover supplied by NASA and developed by JPL, called Muses-CN, onto the surface of the asteroid, but the rover was canceled by NASA in November 2000 due to budget constraints.
- In 2002, launch was postponed from December 2002 to May 2003 to recheck the O-rings of its reaction control system since one of them had been found to be using a different material than specified.
- In 2003, while Hayabusa was en-route to Itokawa, a large solar flare damaged the solar cells aboard the spacecraft. This reduction in electrical power reduced the efficiency of the ion engines, thus delaying the arrival at Itokawa from June to September 2005. Since orbital mechanics dictated that the spacecraft still had to leave the asteroid by November 2005, the amount of the time it was able to spend at Itokawa was greatly reduced and the number of landings on the asteroid was reduced from three to two.
- In 2005, two reaction wheels that govern the attitude movement of Hayabusa failed; the X-axis wheel failed on July 31, and the Y-axis on October 2. After the latter failure, the spacecraft was still able to turn on its X and Y axes with its thrusters. JAXA claimed that since global mapping of Itokawa had been completed, this was not a major problem, but the mission plan was altered. The failed reaction wheels were manufactured by Ithaco Space Systems, Inc, New York, which was later acquired by Goodrich Company.
- The 4 November 2005, 'rehearsal' landing on Itokawa failed, and was rescheduled.
- The original decision to sample two different sites on the asteroid was changed when one of the sites, Woomera Desert, was found to be too rocky for a safe landing.
- The 12 November 2005, release of the MINERVA miniprobe ended in failure.

Mission timeline

Up to the launch

The asteroid exploration mission by ISAS originates in 1986–1987 when the scientists investigated the feasibility of a sample return mission to Anteros and concluded that the technology was not yet developed. Between 1987 and 1994, joint ISAS / NASA group

studied several missions: an asteroid rendezvous mission later became NEAR, and a comet sample return mission later became Stardust.

In 1995, ISAS selected the asteroid sampling as an engineering demonstration mission, MUSES-C, Nereus as the first choice of target, 1989 ML as the secondary choice, and MUSES-C project started in fiscal year 1996. In early development phase, Nereus was considered out of reach and 1989 ML became the primary target. July 2000 failure of M-V forced a delay in the launch from July 2002 to November/December, putting both Nereus and 1989 ML out of reach. As a result, the target asteroid was changed to 1998 SF₃₆. In 2002, launch was postponed from December 2002 to May 2003 to recheck O-rings of reaction control system since one of it was found using different material than specification. On May 9, 2003 04:29:25 UTC, MUSES-C was launched by M-V rocket, and the probe was named "Hayabusa".

Cruising

Ion thruster checkout started on 27 May 2003. Full power operation started on 25 June.

Asteroids are named by their discoverer. ISAS asked LINEAR, the discoverer of 1998 SF₃₆, to offer the name after Hideo Itokawa, and on 6 August, Minor Planet Circular reported that the target asteroid 1998 SF₃₆ was named *Itokawa*.

On October 2003, ISAS and two other national aerospace agencies were merged to form JAXA.

On March 31, 2004, ion thruster operation was stopped to prepare for the Earth swing-by. Last manoeuvre operation before swing-by on May 12. On May 19, Hayabusa performed Earth swing-by. On 27 May, ion thruster operation was started again.

On February 18, 2005, Hayabusa passed aphelion at 1.7 AU. On 31 July, the X-axis reaction wheel failed. On 14 August, Hayabusa's first image of Itokawa was released. The picture was taken by the star tracker and shows a point of light, believed to be the asteroid, moving across the starfield. Other images were taken from 22 to 24 August. On August 28, Hayabusa was switched over from the ion engines to the bi-propellant thrusters for orbital maneuvering. From 4 September, Hayabusa's cameras were able to confirm Itokawa's elongated shape. From September 11, individual hills were discerned on the asteroid. On 12 September, Hayabusa was 20 km from Itokawa and JAXA scientists announced that Hayabusa had officially "arrived".

In proximity of Itokawa

On 15 September, a 'colour' image of the asteroid was released (which is, however, grey in colouring). On 4 October, JAXA announced that the spacecraft had successfully moved to its 'Home Position' 7 km from Itokawa. Closeup pictures were released. It was also announced that the spacecraft's second reaction wheel, governing the Y-axis, had failed, and that the craft was now being pointed by its rotation thrusters. On November 3,

Hayabusa took station 3.0 km from Itokawa. It then began its descent, planned to include delivery of a target marker, and release of the Minerva minilander. The descent went well initially, and navigation images with wide-angle cameras were obtained. However, at 1:50 am UTC (10:50 am JST) on 4 November, it was announced that due to a detection of an anomalous signal at the Go/NoGo decision, the descent, including release of Minerva and the target marker had been canceled. The project manager, Jun-ichiro Kawaguchi, explained that the optical navigation system was not tracking the asteroid very well, probably caused by the complex shape of Itokawa. A few days delay was required to evaluate the situation and reschedule.

On 7 November, Hayabusa was 7.5 km from Itokawa. On November 9, Hayabusa performed a descent to 70 m to test the landing navigation and the laser altimeter. After that, Hayabusa backed off to a higher position, then descended again to 500 m and released one of the target markers into space to test the craft's ability to track it (this was confirmed). From analysis of the closeup images, the Woomera Desert site (Point B) was found to be too rocky to be suitable for landing. The Muses Sea site (Point A) was selected as the landing site, for both first and, if possible, second landings.

On 12 November, Hayabusa closed in to 55 m from the asteroid's surface. MINERVA was released but due to an error failed to reach the surface. On 19 November, Hayabusa landed on the asteroid. There was considerable confusion during and after the maneuver about precisely what had happened, because the high-gain antenna of the probe could not be used during final phase of touch-down, as well as the blackout during handover of ground station antenna from DSN to Usuda station. It was initially reported that Hayabusa had stopped at approximately 10 meters from the surface, hovering for 30 minutes for unknown reasons. Ground control sent a command to abort and ascend, and by the time the communication was regained, the probe had moved 100 km away from the asteroid. The probe had entered into a safe mode, slowly spinning to stabilize attitude. However, after regaining control and communication with the probe, the data from the landing attempt were downloaded and analyzed, and on 23 November, JAXA announced that the probe had indeed landed on the asteroid's surface. Unfortunately, the sampling sequence was not triggered since a sensor detected an obstacle during descent; the probe tried to abort the landing, but since its attitude was not appropriate for ascent, it chose instead a safe descent mode. This mode did not permit a sample to be taken, but there is a high probability that some dust may have whirled up into the sampling horn when it touched the asteroid, so the sample canister currently attached to the sampling horn was sealed. On November 25, a second touchdown attempt was performed. It was initially thought that this time, the sampling device was activated; however, later analysis decided that this was probably another failure and that no pellets were fired. Due to a leak in the thruster system, the probe was put in a "safe hold mode".

On 30 November, JAXA announced that control and communication with Hayabusa had been restored, but a problem remained with the craft's reaction control system, perhaps involving a frozen pipe. Mission control was working to resolve the problem before the craft's upcoming launch window for return to Earth. On December 6, Hayabusa was 550 km from Itokawa. JAXA held a press conference about the situation so far. On 27

November, the probe experienced a power outage when trying attitude correction, probably due to a fuel leakage. On 2 December, an attitude correction was tried, but the thruster did not generate enough force. On 3 December, the probe's Z-axis was found to be 20 to 30 degrees from the sun direction and increasing. On 4 December, as an emergency measure, xenon propellant from the ion engines was blown to correct the spin, and it was confirmed successful. Attitude control was commanded using the xenon gas. On 5 December, attitude was corrected enough to regain communication through the medium gain antenna. Telemetry was obtained and analyzed. As the result of telemetry analysis, it was found that there was a strong possibility that the sampler projectile had not penetrated when it landed on 25 November. Due to the power outage, the telemetry log data was faulty. On 8 December, a sudden attitude change was observed, and communication with Hayabusa was lost. It was thought likely that the turbulence was caused by evaporation of 8 or 10cc of leaked fuel. This forced a wait of a month or two for Hayabusa to stabilize by conversion of precession to pure rotation, after which the rotation axis needed to be directed toward the Sun and Earth within a specific angular range. The probability of achieving this was estimated at 60% by December 2006, 70% by spring 2007.

Recovery and return to Earth

On 7 March 2006, JAXA announced that communication with Hayabusa had been recovered in the following stages: On 23 January, the beacon signal from the probe was detected. On 26 January, the probe responded to commands from ground control by changing beacon signal. On 6 February, an ejection of xenon propellant was commanded for attitude control to improve communication. The spin axis change rate was about two degrees per day. On 25 February, telemetry data was obtained through low-gain antenna. On 4 March, telemetry data was obtained through medium-gain antenna. On 6 March, Hayabusa's position was established at about 13,000 km ahead of Itokawa in its orbit with a relative speed of 3 m per second.

On 1 June, Hayabusa project manager Jun-ichiro Kawaguchi reported that they confirmed two out of four ion engines work normally, which would be sufficient for return journey. On 30 January 2007, Jaxa reported that 7 out of 11 batteries are working and the return capsule was sealed. On 25 April, JAXA reported that Hayabusa started the return journey. On 29 August, it was announced that Ion Engine C onboard Hayabusa, in addition to B and D, has been successfully re-ignited. On 29 October, JAXA reported that the first phase of trajectory maneuver operation has finished and the spacecraft is now put in spin-stabilized state. On 4 February 2009, JAXA reported success in reignition of ion engines and starting second phase of trajectory correction maneuver to return to the Earth. On 4 November 2009, the ion engine D automatically stopped working due to the anomaly from degradation.

On 19 November 2009, JAXA announced that they managed to combine the ion generator of ion engine B and the neutralizer of ion engine A. It is suboptimal but expected to be sufficient to generate the necessary delta-v. Out of 2,200 m/s delta-v necessary to return to the earth, about 2,000 m/s had been performed already, and about

200 m/s still necessary. On 5 March 2010, Hayabusa was on a trajectory that would have passed within the lunar orbit. Ion engine operation was suspended to measure the precise trajectory in preparation to perform Trajectory Correction Maneuver 1 to the Earth-rim trajectory. On 27 March, 06:17 UTC, Hayabusa was on a trajectory which would pass 20,000 km from Earth center, completing the orbit transfer operation from Itokawa to Earth. By 6 April, completed first stage of Trajectory Correction Maneuver (TCM-0) which controlled coarsely to Earth rim trajectory. It was planned to be 60 days before reentry. By 4 May, completed TCM-1 maneuver to control precisely to Earth rim trajectory. On 22 May, TCM-2 started, continued for about 92.5 hours, and finished on 26 May. TCM-3 from 3 through 5 June to change the trajectory from the Earth rim to Woomera, South Australia, TCM-4 was performed on June 9 for about 2.5 hours for a precision control to Woomera Prohibited Area. The reentry capsule was released at 10:51 UTC of 13 June.

Reentry and capsule retrieval



Hayabusa re-entry filmed by a camera onboard NASA's DC-8 Airborne Laboratory. The glowing return capsule is seen forward of and below the main Hayabusa probe bus as the latter breaks up. The heat-shielded capsule continues leaving a wake after the main bus fragments have faded.



The glowing return capsule is seen forward of and below the parent Hayabusa probe bus as the latter breaks up.



The re-entry seen from the Woomera Test Range

The reentry capsule and the spacecraft reentered to the Earth atmosphere on 13 June 2010 at 13:51 UTC. The heat-shielded capsule made a parachute landing in the South Australian outback while the spacecraft broke up and incinerated in a large fireball.

An international team of scientists observed the 12.2 km/s entry of the capsule from 11.9 km (39,000 ft) on board NASA's DC-8 airborne laboratory, using a wide array of imaging and spectrographic cameras to measure the physical conditions during atmospheric reentry in a mission led by NASA's Ames Research Center, with Peter Jenniskens of the SETI Institute as the project scientist.

Since the reaction control system no longer functioned, the 510 kilograms (1,124 lb) space probe re-entered the Earth's atmosphere similar to the approach of an asteroid along with the sample re-entry capsule, and, as mission scientists expected, the majority of the spacecraft disintegrated upon entry.

The return capsule was predicted to land in a 20 km by 200 km area in the Woomera Prohibited Area, South Australia. Four ground teams surrounded this area and located the re-entry capsule by optical observation and a radio beacon. Then a team on board a helicopter was dispatched. They located the capsule and recorded its position with GPS. The capsule was successfully retrieved at 7:08 UTC of 14 June 2010. The two parts of the heat shield, which were jettisoned during the descent, were also found.

After confirming that the explosive devices used for parachute deployment were safe the capsule was packed inside a double layer of plastic bags filled with pure nitrogen gas to

reduce the risk of contamination. The soil at the landing site was also sampled for reference in case of contamination. Then the capsule was put inside a cargo container which had air suspension to keep the capsule below 1.5 G shock during transportation. The capsule and its heat shield parts were transported to Japan by a chartered plane and arrived at the curation facility at the JAXA/ISAS Sagami-hara campus on June 18.

Before the capsule was extracted from the protecting plastic bag, it was inspected using X-ray CT to determine its condition. Then the sample canister was extracted from the reentry capsule. The surface of the canister was cleaned using pure nitrogen gas and carbon dioxide; it was then placed in the canister opening device. The internal pressure of the canister was determined by a slight deformation of the canister as the pressure of the environment nitrogen gas in the clean chamber was varied. The nitrogen gas pressure was then adjusted to match the internal canister pressure to prevent the escape of any gas from the sample upon the opening of the canister.

On October 7, 2010, it was announced that approximately 100 particles were collected by the sample canister, and stated that some may be cosmic materials. The particles are smaller than 0.001 millimeters. Starting in November, JAXA plans the detailed analyses of the samples by splitting each particle and examining their crystal structure at SPring-8.

Confirmation of asteroid particles

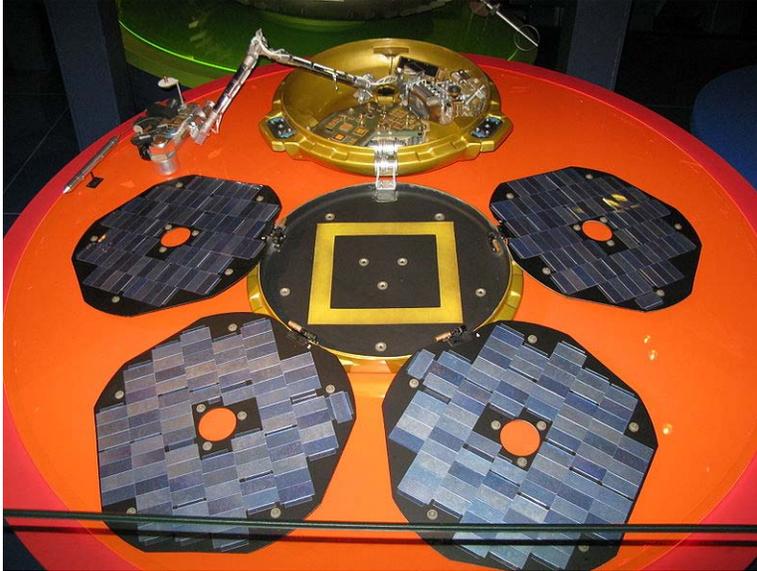
On 16 November 2010, JAXA confirmed that most of the particles found in one of two compartments inside the Hayabusa sample return capsule came from Itokawa. Analysis with a scanning electron microscope identified about 1,500 grains as rocky particles, according to the JAXA press release. After further studying the analysis results and comparison of mineral compositions, most of them were judged to be of extraterrestrial origin, and definitely from the asteroid Itokawa.

According to Japanese scientists, the composition of Hayabusa's samples was more similar to primitive meteorites than known rocks from Earth. Their size is mostly less than 10 micrometers. The material matches chemical maps of Itokawa from Hayabusa's remote sensing instruments. The researchers found concentrations of olivine and pyroxene in the Hayabusa samples.

Further study of the samples will wait until 2011 because researchers are still developing special handling procedures to avoid contaminating the particles during the next phase of research.

Beagle 2

Beagle 2



Operator  European Space Agency

Major contractors  EADS Astrium

Mission type Lander

Launch date 2 June 2003 17:45:00 UTC

Carrier rocket Soyuz-FG/Fregat

Launch site Baikonur Cosmodrome

 Kazakhstan

Mission duration 2003-12-25 03:54:00 UTC
Mission failure on day 206

COSPAR ID 2003-022C

Mass 33.2 kg

Instruments

Data rate 2 or 8kbps / 2 to 128kbps

Beagle 2 was an unsuccessful British landing spacecraft that formed part of the European Space Agency's 2003 *Mars Express* mission. It is not known for certain whether the lander reached the Martian surface; all contact with it was lost upon its separation from the Mars Express six days before its scheduled entry into the atmosphere. It may have

missed Mars altogether, skipped off the atmosphere and entered an orbit around the Sun, or burned up during its descent. If it reached the surface, it may have hit too hard or else failed to make ground contact due to a fault. The *Beagle 2* is named after the *HMS Beagle* which twice carried Charles Darwin during expeditions which would later lead to the theory of evolution.

Background

Beagle 2 was conceived by a group of British academics headed by Professor Colin Pillinger of the Open University, in collaboration with the University of Leicester. Its purpose was to search for signs of life on Mars, past or present, and its name reflected this goal, as Professor Pillinger explained:

"HMS *Beagle* was the ship that took Darwin on his voyage around the world in the 1830s and led to our knowledge about life on Earth making a real quantum leap. We hope *Beagle 2* will do the same thing for life on Mars."

A point at 10.6°N, 270°W in Isidis Planitia, a large flat sedimentary basin that overlies the boundary between the ancient highlands and the northern plains of Mars, was chosen as the landing site. The lander was expected to operate for about 180 days and an extended mission of up to one Martian year (687 Earth days) was thought possible. The *Beagle 2* lander objectives were to characterize the landing site geology, mineralogy, geochemistry and oxidation state, the physical properties of the atmosphere and surface layers, collect data on Martian meteorology and climatology, and search for possible signatures of life.

Pillinger set up a consortium to design and build *Beagle 2*. The principal members and their initial responsibilities were:

- Open University - Consortium leader & scientific experiments
- University of Leicester - Project management, Mission management, Flight Operations Team, instrument management, and scientific experiments
- Astrium - Main industrial partner
- Martin-Baker - Entry, descent and landing system
- Logica - Cruise, entry, descent and landing software
- SciSys - Ground segment and lander software
- University of Wales, Aberystwyth - Robotic arm

In 2000, when the main development phase started, Astrium took over responsibility for program management, and Leicester assumed responsibility for mission management which involved the preparations for the operations post launch and the operations control center.

In an effort to publicize the project and gain financial support, its designers sought and received the endorsement and participation of British artists. The mission's call-sign was composed by the band Blur, and the 'test card' (Calibration Target Plate) intended for

calibrating *Beagle 2*'s cameras and spectrometers after landing was painted by Damien Hirst.

The Lander Operations Control Centre (LOCC) was located at the National Space Centre in Leicester, from which the spacecraft was being controlled, and was visible to the public visiting the center. The control center included operational systems for controlling the *Beagle 2*, analysis tools for processing engineering and scientific telemetry, virtual reality tools for preparing activity sequences, communications systems, and the Ground Test Model (GTM). The GTM was composed of various builds of the *Beagle 2* systems, collected together to provide a full set of lander electronics. The GTM was used nearly continuously to validate the engineering and science commands, to rehearse the landing sequence, and to validate the onboard software.

Spacecraft and subsystems

Beagle 2 had a robotic arm known as the Payload Adjustable Workbench (PAW), designed to be extended after landing. The PAW contained a pair of stereo cameras, a microscope (with a 6 micrometre resolution), a Mössbauer spectrometer, an X-ray spectrometer, a drill for collecting rock samples and a spotlight. Rock samples were to be passed by the PAW into a mass spectrometer and gas chromatograph in the body of the lander - the GAP (Gas Analysis Package), to measure the relative proportions of different isotopes of carbon. Since carbon is thought to be the basis of all life, these readings could have revealed whether the samples contained the remnants of living organisms.

In addition, *Beagle 2* was equipped with a small "mole" (Planetary Undersurface Tool, or PLUTO), to be deployed by the arm. PLUTO had a compressed spring mechanism designed to enable it to move across the surface at a rate of 20 mm per second and to burrow into the ground and collect a subsurface sample in a cavity in its tip. The mole was attached to the lander by a power cable which could be used as a winch to bring the sample back to the lander.

The lander had the shape of a shallow bowl with a diameter of 1m and a depth of 0.25 m. The cover of the lander was hinged and folded open to reveal the interior of the craft which holds a UHF antenna, the 0.75 m long robot arm, and the scientific equipment. The main body also contained the battery, telecommunications, electronics, and central processor, heaters, and additional payload items (radiation and oxidation sensors). The lid itself further unfolded to expose four disk-shaped solar arrays. The lander package had a mass of 69 kg at launch but the actual lander would have been only 33.2 kg at touchdown.

The ground segment itself was derived from the European Space Agency software kernel known as SCOS2000. In keeping with the low cost theme of the mission, the control software was the first of its type deployed on a laptop.

Mission profile

Mars Express launched from Baikonur on 2 June 2003, at 17:45 UTC (18:45 BST). The *Beagle 2* was a Mars lander initially mounted on the top deck of the *Mars Express Orbiter*. It was released from the *Orbiter* on a ballistic trajectory towards Mars on the 19th of December 2003 at 8:31 UT. *Beagle 2* coasted for six days after release and was scheduled to enter the Martian atmosphere, at over 20,000 km/h, on the morning of the 25th of December. The lander was protected from the heat of entry by a heatshield coated with NORCOAT, an ablating material made by EADS. Compression of the martian atmosphere and radiation from the hot gas are estimated to have led to a peak heating rate of around 100 W/cm², comparable to the heat flux experienced by Mars Pathfinder.

After deceleration in the Martian atmosphere, parachutes were to be deployed and about 1 km above the surface large airbags were to inflate around the lander and protect it when it hit the surface. Landing was expected to occur at about 02:45 UT on 25 December (9:45 p.m. EST 24 December). After landing the bags were supposed to deflate and the top of the lander was to open. A signal was supposed to be sent to *Mars Express* after landing and another the next (local) morning to confirm that *Beagle 2* survived the landing and the first night on Mars. A panoramic image of the landing area was then supposed to be taken using the stereo camera and a pop-up mirror, after which the lander arm would have been released. The lander arm was to dig up samples to be deposited in the various instruments for study, and the "mole" would have been deployed, crawling across the surface to a distance of about 3 metres from the lander and burrowing under rocks to collect soil samples for analysis.

The British government spent more than £22 million (US\$40 million) on *Beagle 2*, with the remainder of the total £44 million (US\$80 million) coming from the private sector.

Mission progress

Although the *Beagle 2* craft successfully deployed from the *Mars Express* "mother ship", confirmation of a successful landing was not forthcoming. Confirmation should have come on 25 December 2003, when the *Beagle 2* should have contacted NASA's 2001 *Mars Odyssey* spacecraft that was already in orbit. In the following days, the Lovell Telescope at Jodrell Bank also failed to pick up a signal from *Beagle 2*. The team said they were "still hopeful" of finding a successful return signal.

Attempts were made throughout January and February 2004 to contact *Beagle 2* using *Mars Express*. The first of these occurred on 7 January 2004, but ended in failure. Although regular calls were made, particular hope was placed on communication occurring on 12 January, when *Beagle 2* was pre-programmed to expect the *Mars Express* probe to fly overhead, and on 2 February, when the probe was supposed to resort to the last communication back-up mode: Autotransmit. However, no communication was ever established with *Beagle 2*. *Beagle 2* was declared lost on 6 February 2004, by

the *Beagle 2* Management Board. On 11 February, ESA announced an inquiry would be held into the failure of *Beagle 2*.

On 20 December 2005, Professor Pillinger released specially-processed images from the Mars Global Surveyor which suggested that *Beagle 2* came down in a crater at the landing site on Isidis Planitia. It was claimed that the blurry images show the primary impact site as a dark patch and a short distance away, *Beagle 2* surrounded by the deflated airbags and with its solar panels extended. However, Mars Reconnaissance Orbiter's HiRISE camera subsequently observed the area, in February 2007, and revealed that the crater was empty.

Failures in missions to Mars are common. As of 2010, of 38 launch attempts to reach the planet, only 19 have succeeded.

ESA/UK inquiry report

In May 2004, the report from the Commission of Inquiry on *Beagle 2* was submitted to ESA and the UK's science minister Lord Sainsbury. Initially the full report was not published on the grounds of confidentiality, but a list of 19 recommendations was announced to the public.

Professor David Southwood, ESA's director of science, provided four scenarios of possible failures:

- *Beagle* entered in atmospheric conditions outside the range assumed by its designers and could have burnt up. The scenario that it may have "bounced off into space" has been put forward but this does not stand up to close technical scrutiny. The amount of dust in the atmosphere often varies widely, changing its density and temperature characteristics. However, the chosen margins on the design of the heat shield and the thermal loads it can withstand are such that the burn-up scenario is unlikely, and even the worst case density variations certainly are not such that, given the steep entry flight path angle at entry, the craft could conceivably have left the atmosphere again;
- The probe's parachute or cushioning airbags failed to deploy or deployed at the wrong time. This is supported by the observation that throughout the transfer to Mars, the outgassing of some substance and subsequent condensation on optical components of the Mars Express spacecraft carrying the Beagle lander was observed. This observation would be consistent with a leak in the gas generators of Beagle's airbags;
- *Beagle's* backshell tangled with the parachute preventing it from opening properly. It is not clear whether the difference in air drag between the probe with the parachute deployed and the back shell of the heat shield is sufficient to guarantee a safe separation distance;
- *Beagle* became wrapped up in its airbags or parachute on the surface and could not open. Entanglement with the parachute appears plausible in view of the fact that the parachute's strop was shortened from the original design to save mass.

Assuming that the airbags deployed, Beagle would, in the scenario, have bounced off the surface right back into the descending parachute;

In addition, further scenarios appear plausible and consistent with the available body of data:

- *Beagle* may have jettisoned its airbags too early, before it had come to a complete rest on the surface. For mass and cost reasons, the airbag jettison device was designed to be triggered by a timer rather than by acceleration sensors that would have discerned when the lander package had stopped moving. Given that the landing package of NASA's Spirit rover mission rebounded off the surface in Gusev crater numerous times before coming to a standstill - taking much more time than anticipated -, *Beagle's* timer may have been set to a too short time;
- The parachute deployment sequence was designed triggered by three accelerometers. The system was not designed for a "best out of three" logic. Rather, the first accelerometer to compute that a safe deployment velocity had been reached would trigger the parachute deployment sequence, even if the accelerometer readout were faulty;

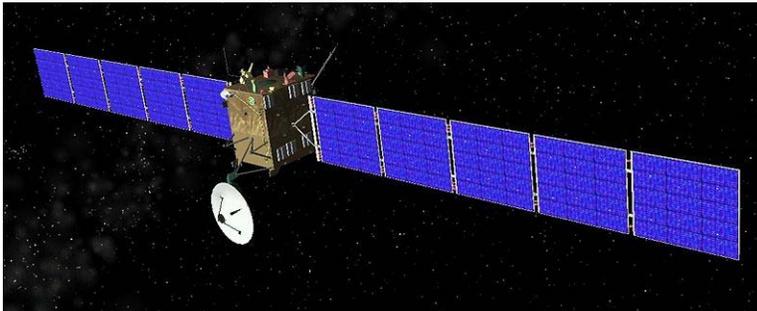
In February 2005, following comments from the House of Commons Select Committee on Science and Technology, the report was made public, and Leicester University independently published a detailed mission report, including possible failure modes, and a "lessons learned" pamphlet.

Chapter- 4

Space and Solar System Exploration in 2004

Rosetta (spacecraft)

Rosetta



Operator	European Space Agency
Major contractors	European Space Agency
Mission type	Comet Orbiter/Lander
Flyby of	Earth, Mars, 2867 Šteins, 21 Lutetia
Satellite of	67P/Churyumov-Gerasimenko
Launch date	March 2, 2004 at 07:17 UTC
Launch vehicle	Ariane 5G+
Mission duration	6 years, 10 months, and 12 days elapsed
Orbital decay	N/A
COSPAR ID	2004-006A

Rosetta is a robotic spacecraft of the European Space Agency on a mission to study the comet 67P/Churyumov-Gerasimenko. Rosetta consists of two main elements: the **Rosetta space probe** and the **Philae lander**. The spacecraft was launched on 2 March 2004 on an

Ariane V rocket and will reach the comet by mid 2014. The space probe is intended to orbit and perform long-term exploration of the comet at close quarters. On 10 November 2014 the Philae lander will attempt to land and perform detailed investigations on the comet's surface. Both the probe and the lander carry a large complement of scientific experiments designed to complete the most detailed study of a comet ever attempted.

The probe is named after the Rosetta Stone, as it is hoped the mission will help unlock the secrets of how our solar system looked before planets formed. The lander is named after the Nile island Philae where an obelisk was found that helped decipher the Rosetta Stone. The spacecraft has already performed two successful asteroid flyby missions on its way to the comet. The craft completed its fly-by of asteroid 2867 Šteins in September 2008 and of 21 Lutetia in July 2010, and is presently functioning and on-target for its final destination as of late 2010.

Mission timeline

This is the planned timeline for the mission after its launch:

- First Earth flyby (March 4, 2005)
- Mars flyby (February 25, 2007)
- Second Earth flyby (November 13, 2007)
- Flyby of asteroid 2867 Šteins (September 5, 2008)
- Third Earth flyby (November 13, 2009)
- Flyby of asteroid 21 Lutetia (July 10, 2010)
- Deep-space hibernation (May 2011 - January 2014)
- Comet approach (January-May 2014)
- Comet mapping / Characterisation (August 2014)
- Landing on the comet (November 2014)
- Escorting the comet around the Sun (November 2014 - December 2015)

Overview

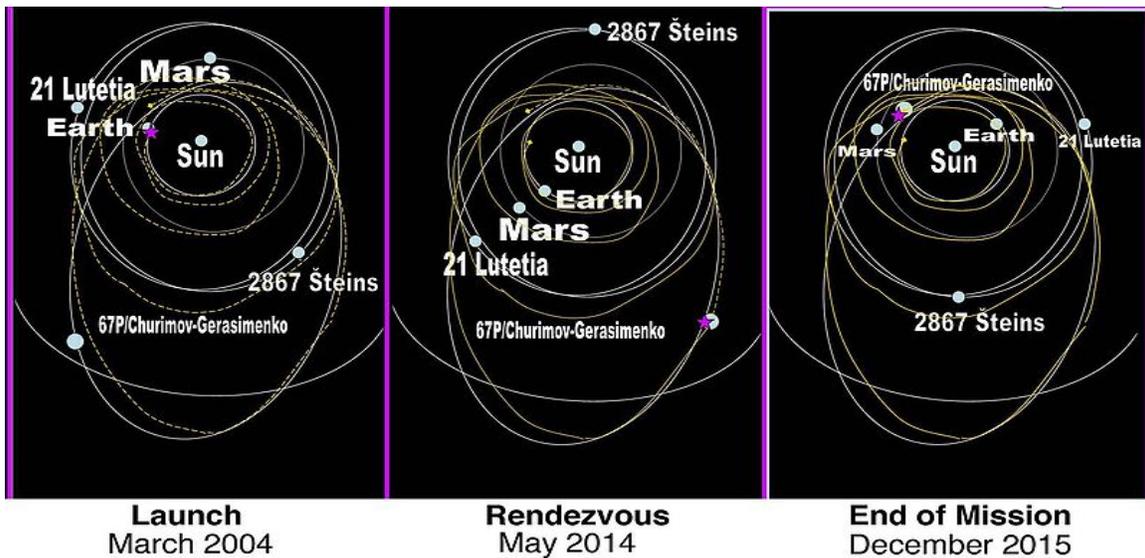
During the 1986 apparition of the Comet Halley, a number of international space probes were sent to explore the cometary system, most prominent among them being ESA's highly successful Giotto. After the probes returned a treasure-trove of valuable scientific information it was becoming obvious that follow-ons were needed that would shed more light on the complex cometary composition and resolve the newly opened questions.

Both NASA and ESA started cooperatively developing new probes. The NASA project was the Comet Rendezvous Asteroid Flyby or CRAF mission. The ESA project was the follow-on Comet Nucleus Sample Return (CNSR) mission. Both missions were to share the Mariner Mark II spacecraft design, thus minimizing costs. In 1992, after NASA axed CRAF due to budgetary limitations, ESA decided to develop a CRAF-style project on its own. By 1993 it was evident that the ambitious sample return mission was unfeasible with the existing ESA budget, so the mission was redesigned, with the final flight plan

resembling the canceled CRAF mission, an asteroid flyby followed by a comet rendezvous with in-situ examination, including a lander.

Rosetta was built in a clean room according to COSPAR rules, but "Sterilisation [was] generally not crucial since comets are usually regarded as objects where you can find prebiotic molecules, that is, molecules that are precursors of life, but not living microorganisms, " according to Gerhard Schwehm, Rosetta's Project Scientist.

It was set to be launched on January 12, 2003 to rendezvous with the comet 46P/Wirtanen in 2011.



Trajectory of the Rosetta Space Probe

However, this plan was abandoned after a failure of the planned launch vehicle Ariane 5 on December 11, 2002. A new plan was formed to target the comet Churyumov-Gerasimenko, with launch on February 26, 2004 and rendezvous in 2014. The larger mass and the resulting increased impact velocity made modification of the landing gear necessary. After two cancelled launch attempts, Rosetta was launched on March 2, 2004 at 7:17 GMT. Besides the changes made to launch time and target, the mission profile remains almost identical.

The first flyby of Earth occurred on March 4, 2005.

On February 25, 2007, the craft was scheduled for a low-altitude bypass of Mars, to correct the trajectory after the first launch in 2003 was delayed by one year. This was not without risk, as the estimated altitude of the flyover manoeuvre was a mere 250 km (155 miles). During that encounter the solar panels could not be used since the craft was in the planet's shadow, where it would not receive any solar light for 15 minutes, causing a dangerous shortage of power. The craft was therefore put into standby mode, with no possibility to communicate, flying on batteries that were originally not designed for this

task. This Mars manoeuvre was therefore nicknamed "The Billion Dollar Gamble". Fortunately, the flyby was successful and the mission continued as planned.

The second Earth flyby occurred on November 13, 2007.

The spacecraft performed a close flyby of asteroid 2867 Šteins on September 5, 2008. Its onboard cameras were used to fine-tune the trajectory, achieving a minimum separation of less than 800 km (497 miles). Onboard instruments measured the asteroid from August 4 to September 10. Maximum relative speed between the 2 objects during the flyby was 8.6 km/s (19,240 mph).

Rosetta's third and final flyby of Earth happened on November 12, 2009.

The asteroid's orbit was known before Rosetta's launch, from ground-based measurements, to an accuracy of approximately 100 km. Information gathered by the onboard cameras beginning at a distance of 24 million km will be processed at ESA's Operation Center to refine the asteroid's position in its orbit to a few km.

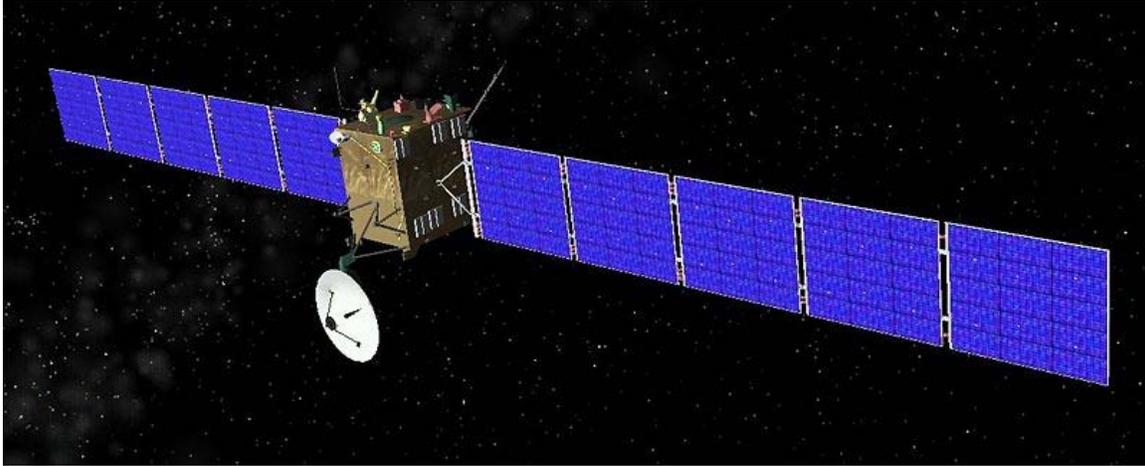
In May 2014, the *Rosetta* craft will enter a slow orbit around the comet and gradually slow down in preparation for releasing a lander that will make contact with the comet itself. The lander, named "Philae", will approach Churyumov-Gerasimenko at relative speed around 1 m/s and on contact with the surface, two harpoons will be fired into the comet to prevent the lander from bouncing off. Additional drills are used to further secure the lander on the comet.

Once attached to the comet, expected to take place in November 2014, the lander will begin its science mission:

- Characterisation of the nucleus
- Determination of the chemical compounds present, including enantiomers
- Study of comet activities and developments over time

The exact surface layout of the comet is currently unknown and the orbiter has been built to map this before detaching the lander. It is anticipated that a suitable landing site can be found, although few specific details exist regarding the surface.

Instruments



Computer model of Rosetta probe

Core

The spectroscopical investigation of the core is done by four instruments.

- **ALICE** (an ultraviolet imaging spectrograph). The UV spectrograph will search for the abundance of noble gas in the comet core, from which the temperature during the comet creation could be estimated. The detection is done by an array of potassium bromide and caesium iodide photocathodes. The 3.1 kg instrument uses 2.9 watts and was produced in the USA, and an improved version is used in the New Horizons.
- **OSIRIS** (Optical, Spectroscopic, and Infrared Remote Imaging System). The camera system has a narrow angle lens (700 mm) and a wide angle lens (140 mm), with a 2048x2048 pixel CCD chip. The instrument was constructed in Germany.
- **VIRTIS** (Visible and Infrared Thermal Imaging Spectrometer). The Visible and IR spectrometer is able to make pictures of the core in the IR and also search for IR spectra of molecules in the coma. The detection is done by a mercury cadmium teluride array for IR and with a CCD chip for the Visible range. The instrument was produced in Italy, and improved versions were used for Dawn and Venus express.
- **MIRO** (Microwave Instrument for the Rosetta Orbiter). The abundance and temperature of volatile substances like water, ammonia and carbon dioxide can be detected by MIRO via their microwave emissions. The 30 cm radio antenna was constructed in Germany, while the rest of the 18.5 kg instrument was provided by the USA.

The interior of the comet is probed by the CONSERT instrument.

- **CONSERT** (Comet Nucleus Sounding Experiment by Radiowave Transmission). The CONSERT experiment is the only experiment on board the ROSETTA mission which will provide information about the deep interior of the comet. The Consert radar will perform tomography of the nucleus by measuring electromagnetic wave propagation between the Philae lander and the Rosetta orbiter through the comet nucleus. This allows it to determine the comet's internal structure and deduce information on its composition. The lander and orbiter electronics were provided by France and both antennas were constructed in Germany.

Gas and particles

- **ROSINA** (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis). The instrument consists a double focus magnetic mass spectrometer DFMS and a reflectron type time of flight mass spectrometer RTOF. The DFMS has a high resolution (can resolve N₂ from CO) for molecules up to 300 amu. The RTOF is highly sensitive for neutral molecules and for ions.
- **MIDAS** (Micro-Imaging Dust Analysis System). The high resolution atomic force microscope will investigate the dust particles which are deposited on a silicone plate.
- **COSIMA** (Cometary Secondary Ion Mass Analyser). COSIMA analyses the composition of dust particles by secondary ion mass spectrometry, after the surface is cleaned by indium ions. It can analyse ions up to a mass of 4000 amu.

Solarwind interaction

- **GIADA** (Grain Impact Analyser and Dust Accumulator)
- **RPC** (Rosetta Plasma Consortium).

Major events and discoveries

2004

- March 2 – ESA's *Rosetta* mission was successfully launched at 07:17 UTC (08:17 Central European Time). The launcher successfully placed its upper stage and payload into an eccentric coast orbit (200 x 4,000 km). About two hours later, at 09:14 UTC, the upper stage ignited its own engine to reach escape velocity in order to leave the Earth's gravity field and enter heliocentric orbit. The Rosetta probe was released 18 minutes later. ESA's Operations Centre (ESOC) in Darmstadt, Germany, established contact with the probe shortly after that.
- May 10 – The first and most important deep space maneuver was successfully executed to adjust the course of the space craft, with a reported inaccuracy of 0.05%.

2005

- March 4 – *Rosetta* executed its first planned close flyby of Earth. The Moon and the Earth's magnetic field were used to test and calibrate the instruments on board of the spacecraft. The minimum altitude above the Earth's surface was about 1,954.7 km at 22:09 UTC and images of the space probe passing by were captured by amateur astronomers.
- July 4 – Imaging instruments on board observed the collision between the comet Tempel 1 and the impactor of the Deep Impact mission.

2007

- February 25 – Mars swing-by. Philae's ROMAP (Rosetta Lander Magnetometer and Plasma Monitor) instrument measures the complex Martian magnetic environment, while Rosetta's OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) took various images of the planet using different photographic filters. While in Mars' shadow most of the instruments were turned off the Philae lander was autonomously running on batteries. During this operation the ČIVA instrument on the lander took pictures of Mars. Among others, both actions were meant to test the spacecraft's instruments. The space craft used the gravity of Mars to change course towards its second Earth flyby in November.
- November 8 – Misidentification of Rosetta space craft as an asteroid (see below).

2008

- September 5 – Flyby of asteroid 2867 Šteins. The spacecraft passed the main-belt asteroid at a distance of 800 km and the relatively slow speed of 8.6 km/s.

2009

- November 13 – Last swingby (gravity assist passage) of Earth. The spacecraft made its closest approach (perigee passage) at 2481 km altitude over 109°E and 8°S - just off the coast of the Indonesian island of Java, at 07:45 UTC.

2010

- March 16 - Observation of the dust tail of the asteroid P/2010 A2. Together with observations of Hubble space telescope it could be confirmed that the P/2010 A2 is not a comet but an asteroid and the tail most likely consists of particles from an impact of a smaller asteroid.
- July 10 - Flew by and photographed the asteroid 21 Lutetia.

Misidentification as an asteroid

In November, 2007, during its second flyby, the Rosetta spacecraft was mistaken for a dangerous near-Earth asteroid and given the designation **2007 VN₈₄**. Based upon images taken by a 0.68 meter telescope of the Catalina Sky Survey, an astronomer 'discovered' the spacecraft and misidentified it as an asteroid about 20 meters in diameter, and performed a trajectory calculation showing that it would make its closest flyby of the Earth at a distance of 5,700 kilometers on November 13, 2007. This extremely close approach (in astronomical terms) led to speculation that 2007 VN₈₄ might be at risk of impacting the Earth. However, astronomer Denis Denisenko recognized that the trajectory matched that of the Rosetta probe, which was performing a flyby of Earth en route to its rendezvous with a comet. The Minor Planet Center later confirmed in an editorial release that 2007 VN₈₄ was actually the spacecraft.

MESSENGER

MESSENGER



Technicians prepare MESSENGER for transfer to a hazardous processing facility prior to loading the spacecraft's complement of hypergolic propellants.

Operator	NASA
Major contractors	APL
Mission type	Orbiter / Fly-by

Flyby of	Earth, Venus, Mercury
Satellite of	Mercury
Orbital insertion date	2011-03-18 02:14:00 UTC (projected)
Launch date	2004-08-03 06:15:56 UTC (6 years, 167 days ago)
Launch vehicle	Delta II 7925H-9.5
Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
Mission duration	In Transit
COSPAR ID	2004-030A
Mass	1,093 kg (2,410 lb)
Power	450 W (Solar array / 11 NiH ₂ batteries)

The **MERcury Surface, Space ENvironment, GEOchemistry and Ranging (MESSENGER)** probe is a spacecraft of the United States space agency NASA, launched August 3, 2004 to study the characteristics and environment of Mercury from orbit. Specifically, the mission is to characterize the chemical composition of Mercury's surface, the geological history, the nature of the magnetic field, the size and state of the core, the volatile inventory at the poles, and the nature of Mercury's exosphere and magnetosphere over a nominal orbital mission of one Earth year.

The mission is the first to visit Mercury in over 30 years; the only previous probe to visit Mercury was Mariner 10, which completed its mission in March 1975. The MESSENGER has vastly improved scanning capability, with cameras capable of resolving surface features to 18 m (59 ft) across compared to the 1.6 km (0.99 mi) resolution of the Mariner 10. MESSENGER is an orbital mission, and will spend over a year imaging the entire planet; Mariner 10 was a flyby mission and was only able to observe the one hemisphere that was lit during its flybys.

The contrived acronym MESSENGER was chosen because Mercury was the messenger of the gods according to Roman mythology.

Travel to Mercury



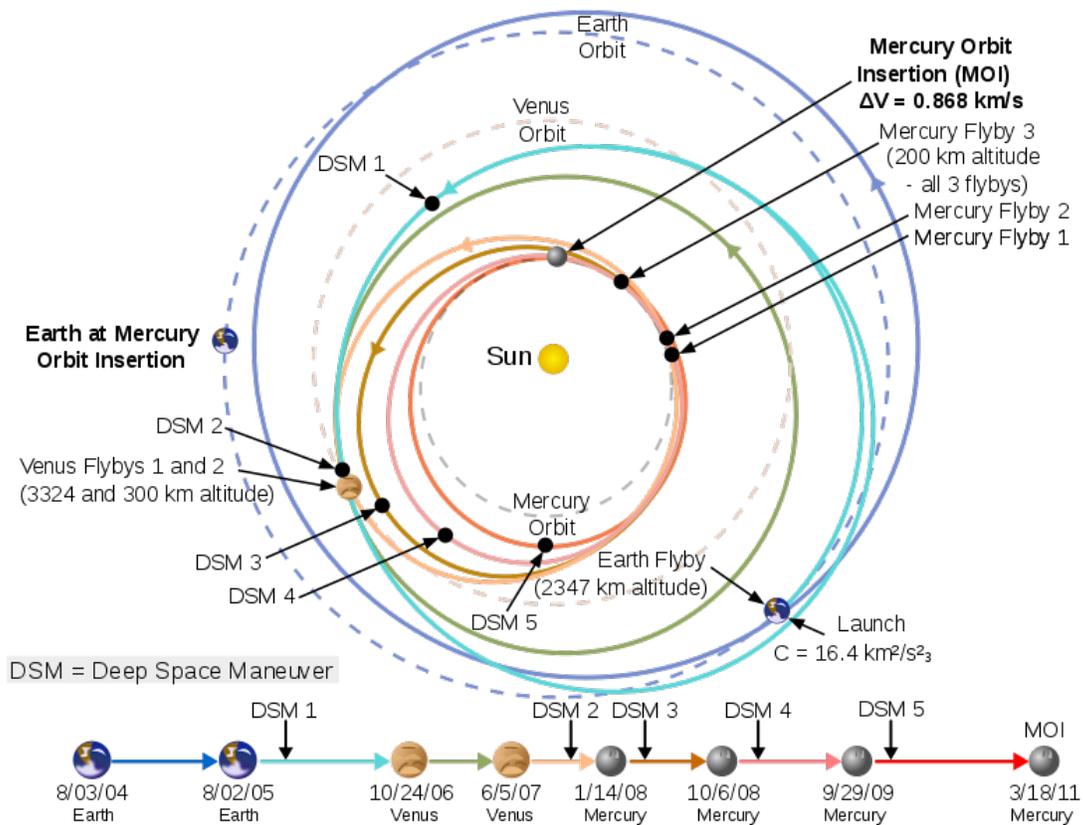
The launch of MESSENGER

The Boeing Delta II rocket carrying MESSENGER lifted off from Cape Canaveral Air Force Station, Florida at 02:15:56 EDT on August 3, 2004. An hour later, NASA confirmed that MESSENGER had successfully separated from the third stage booster and commenced its roundabout route to Mercury.

Travel to Mercury requires an extremely large velocity change, or delta-v, because Mercury lies deeper in the Sun's gravity well; a spacecraft traveling to Mercury is greatly accelerated as it falls toward the Sun, so there must be a mechanism to slow it. Mercury

does not have an atmosphere thick enough to aerobrake on arrival. To make the trip feasible, MESSENGER makes extensive use of gravity assist maneuvers. These reduce the amount of rocket fuel needed to slow down, but greatly prolong the trip. For additional fuel savings, the thrust used for insertion into orbit about Mercury will be minimized, resulting in a notably elliptical orbit. Besides the advantage of saving fuel, such an orbit allows the spacecraft to measure solar wind and magnetic fields at a variety of distances from the planet, yet still get close-up measurements and photographs of the surface.

MESSENGER performed a successful Earth swing-by a year after launch, on 2 August 2005, with the closest approach at 19:13 UTC at an altitude of 2,347 kilometers (1,458 statute miles) over central Mongolia. On December 12, 2005, a 524 second long burn (Deep-Space Maneuver or DSM-1) of the large thruster adjusted the trajectory for the upcoming Venus swing-by.



MESSENGER's trajectory



A view of Earth from MESSENGER during its Earth swing-by

MESSENGER made its first flyby of Venus at 08:34 UTC on October 24, 2006 at an altitude of 2,992 kilometers (1,859 mi). A second flyby of Venus was made at 23:08 UTC on June 5, 2007 at an altitude of 338 kilometers (210 mi). On October 17, 2007, Deep-Space Maneuver 2 or DSM-2' was executed successfully, putting MESSENGER on target for its first flyby of Mercury. MESSENGER made a flyby of Mercury on 14 January 2008 (closest approach 200 km above surface of Mercury at 19:04:39 UTC), followed by a second flyby on October 6, 2008. MESSENGER executed one last flyby on September 29, 2009, that further slowed down the spacecraft. Both the second and third flybys were preceded by DSM-3 on 19 March 2008 at 19:30 UTC and DSM-4 on 04 December, 2008 at 20:30 UTC to adjust the velocity of the spacecraft. One last deep space maneuver, DSM-5 was executed on November 24, 2009 at 22:45 UTC to provide the required velocity change for the scheduled Mercury orbit insertion on March 18, 2011, marking the beginning of a year-long orbital mission.

All along the way, numerous trajectory corrections were made to MESSENGER's course. The corrections numbered 35 as of 24, November 2009 and are referred to as TCM or Trajectory Correction Maneuver. TCM which use the large bi-propellant thrusters are also referred to as DSM or Deep Space Maneuver. DSM generally concern major adjustments to the spacecraft's velocity while TCM usually deal with modifying the craft's orientation with respect to the Sun (crucial for thermal management) and targeting aim points for flybys of planets.

During the Earth flyby, MESSENGER imaged the Earth and Moon and used its atmospheric and surface composition spectrometer to look at the Moon. The particle and magnetic field instruments investigated the Earth's magnetosphere.

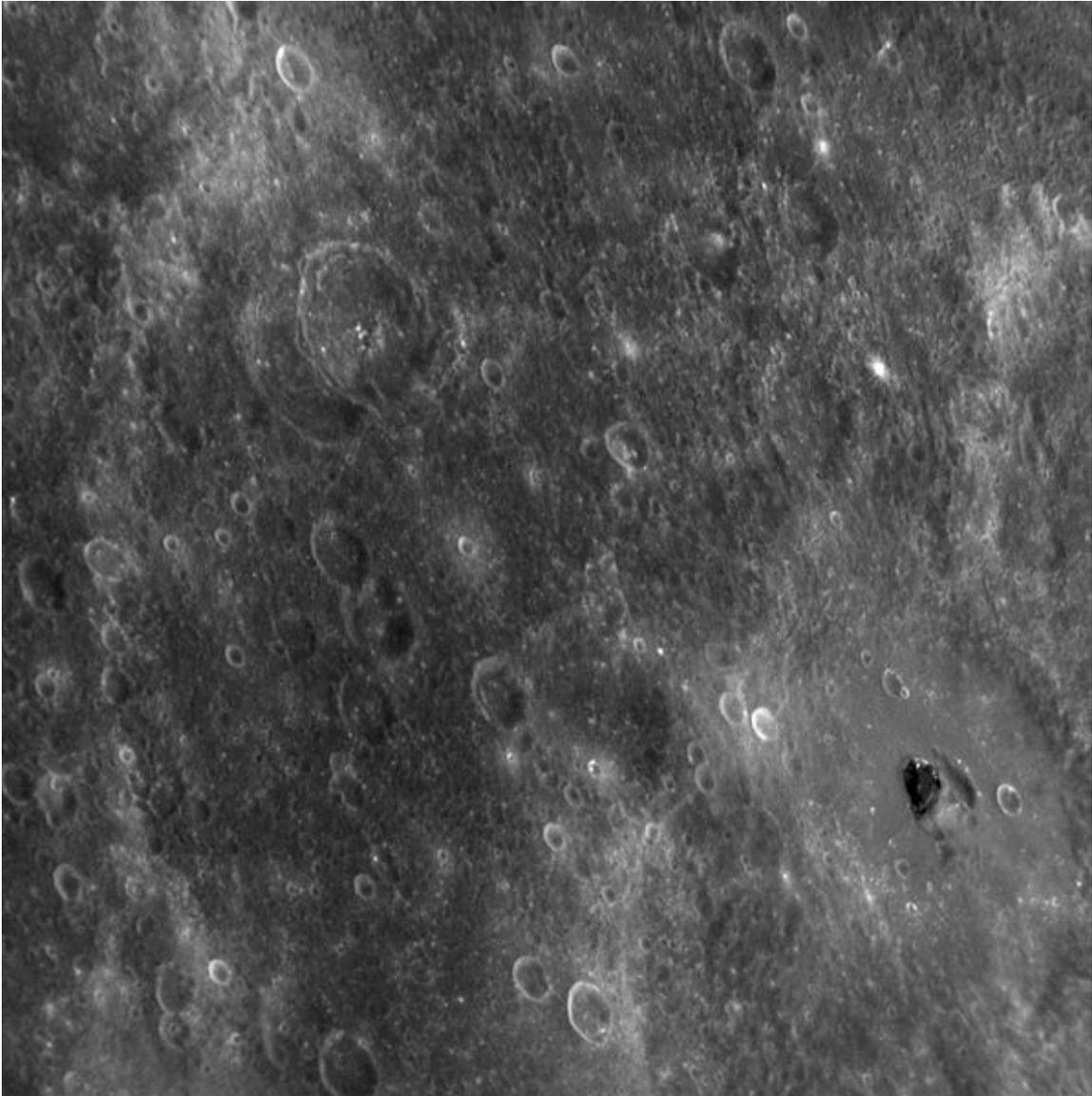
The spacecraft was originally scheduled to launch during a 12-day window that opened May 11, 2004, but on March 26, 2004, NASA announced that a later launch window starting at July 30, 2004 with a length of 15 days would be used. This was to allow more time for testing and spacecraft processing. This change significantly altered the trajectory of the mission and delayed the arrival at Mercury by two years. The original plan called for three fly-by maneuvers past Venus, with Mercury orbit insertion scheduled for 2009. The new trajectory features one Earth flyby, two Venus flybys, and three Mercury flybys before orbit insertion on March 18, 2011.

The navigation team is led by KinetX, Inc. of Tempe, Arizona. KinetX is the first private company to be responsible for navigation of a NASA deep space mission. In that role, they are responsible for determining all trajectory adjustments throughout the probe's flight through the inner solar system ensuring that MESSENGER arrives at Mercury with the proper velocity for orbit insertion.

Mercury observation plan



MESSENGER's first image of the side of Mercury which was never seen by Mariner 10, from a distance of about 17,000 miles (27,000 km)



An unidentified patch of black on Mercury

The nominal orbit has a periapsis of 200 km (120 mi) at 60 degrees N latitude, and an apoapsis of 15,193 km (9,440 mi), a period of 12 hours and an inclination of 82.5 degrees. The periapsis will slowly rise due to solar perturbations to over 400 km (250 mi) at the end of 88 days (one Mercury year) at which point it will be readjusted to a 200 km (120 mi), 12 hour orbit via a two burn sequence. Data will be collected from orbit for one Earth year, the nominal end of the primary mission. Global stereo image coverage at 250 meters/pixel resolution is expected. The mission should also yield global composition maps, a 3-D model of Mercury's magnetosphere, topographic profiles of the northern hemisphere, gravity field to degree and order 16, altitude profiles of elemental species, and a characterization of the volatiles in permanently shadowed craters at the poles.

Once there, scientists hope to test a theory that the planet is shrinking, contracting on itself as its core slowly freezes. The probe will look for signs of surface buckling on Mercury's unobserved hemisphere, as well as collect surface composition data on material that may have once spewed out of the planet's interior. The idea that Mercury's surface was somehow shrinking arose when Mariner 10 returned images of great scarps biting deep into the planet's surface. One such scarp, Discovery Rupes, cuts 1.6 km (1 mi) into Mercury's crust.

Spacecraft and subsystems



MESSENGER assembly installation of solar panels Astrotech

MESSENGER was designed and built by the Johns Hopkins University Applied Physics Laboratory (JHU/APL). It is a squat box (1.27 m × 1.42 m × 1.85 m) with a semi-cylindrical thermal shade for protection from the Sun and two solar panel wings extending radially. A 3.6 m (12 ft) magnetometer boom also extends from the craft. The total mass of the spacecraft is 1,093 kg (2,410 lb); 607.8 kg (1,340 lb) of this is propellant (hydrazine and nitrogen tetroxide) and helium. The structure is primarily graphite cyanate ester (GrCE) composite and consists of two vertical panels which support two large fuel tanks and two vertical panels which support the oxidizer tank and plumbing panel. The four vertical panels make up the center column and are bolted at their aft ends to an aluminum adapter. A single top deck panel mounts the LVA (large velocity adjust) thruster, small thrusters, helium and auxiliary fuel tanks, star trackers and battery.

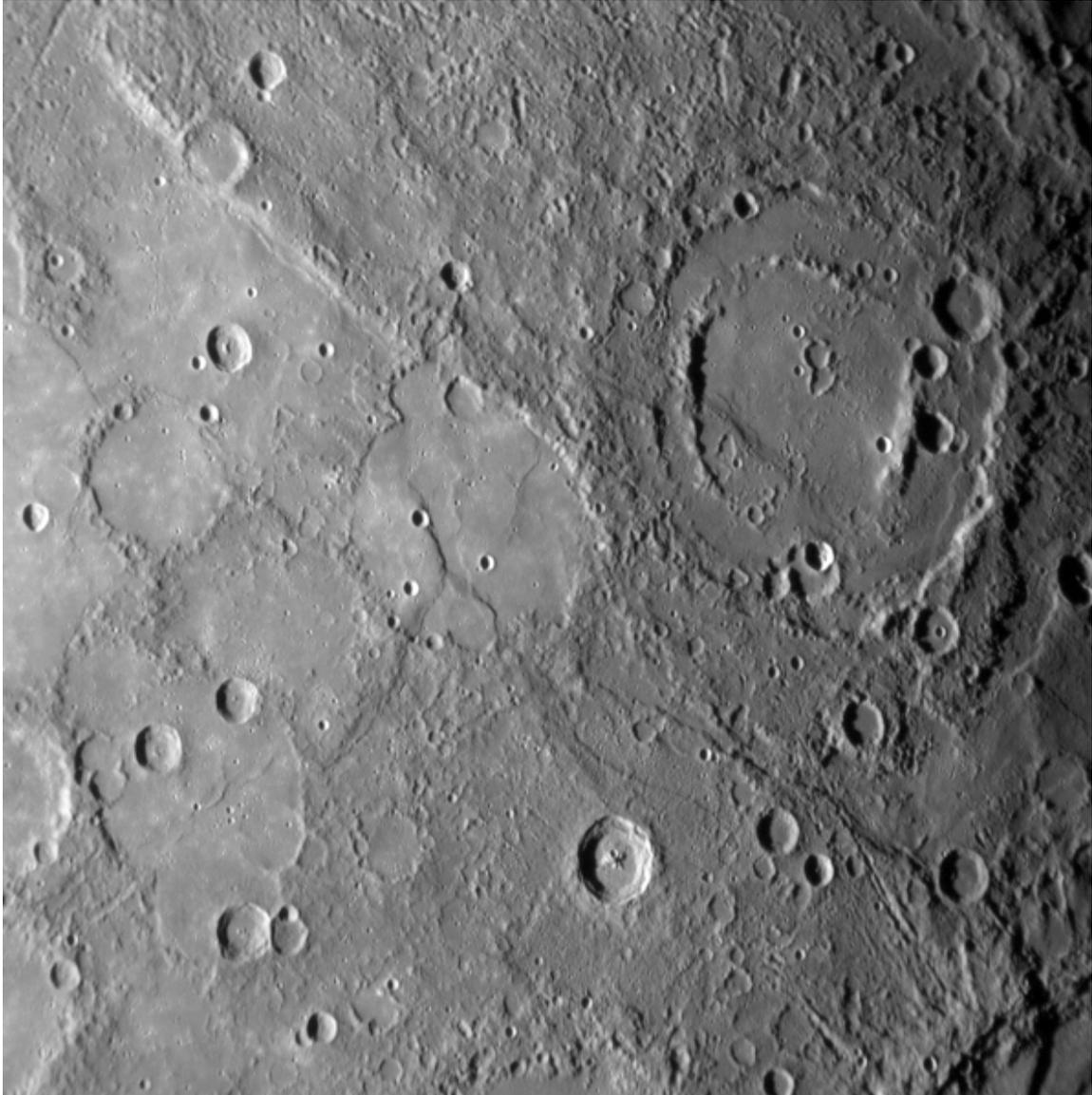
Main propulsion is via the 645 N (145 lbf), 317 s bipropellant LVA thruster. Four 22 N (4.9 lbf) monopropellant thrusters provide spacecraft steering during main thruster burns, and ten 4 N (0.9 lbf) monopropellant thrusters are used for attitude control. There is also a reaction wheel attitude control system. Information for attitude control is provided by star tracking cameras, an inertial measurement unit, and six solar sensors. Power is provided by solar panels which extend beyond the sunshade. They are rotatable to balance panel temperature and power generation and provide a nominal 450 watts in Mercury orbit. The panels are 70 percent optical solar reflectors and 30 percent GaAs/Ge cells. The power is stored in a common-pressure-vessel, 23-ampere-hour nickel hydrogen battery, with 11 vessels and two cells per vessel.

Communications uses two small deep space transponders (SDSTs) operating at X-band. Downlink is through two fixed phased array antenna clusters, and uplink and downlink through medium- and low-gain antennas on the forward and aft sides of the spacecraft. Passive thermal control, primarily a fixed opaque ceramic cloth sunshade, is utilized to maintain operating temperatures near the Sun. Radiators are built into the structure and the orbit is optimized to minimize infrared and visible light heating of the spacecraft from the surface of Mercury. Multilayer insulation, low conductivity couplings, and heaters are also used to maintain temperatures within operating limits.

Five science instruments are mounted externally on the bottom deck of the main body: the Mercury Dual Imaging System (MDIS), Gamma-Ray and Neutron Spectrometer (GRNS), X-ray Spectrometer (XRS), Mercury Laser Altimeter (MLA), and Atmospheric and Surface Composition Spectrometer (MASCS). The Energetic Particle and Plasma Spectrometer (EPPS) is mounted on the side and top deck and the magnetometer (MAG) is at the end of the 3.6 meter boom. Radio Science (RS) experiments will use the existing communications system.

MESSENGER's onboard computer system is based on the Integrated Electronics Module (IEM), a device that combines core avionics in a single box. The spacecraft carries a pair of identical IEMs for backup purposes; both house a 25 megahertz main processor and 10 MHz fault protection processor. All four are radiation-hardened IBM RAD6000 processors, based on the IBM POWER1 CPU architecture (similar to that of older Macintoshes). The RAD computer is slow by current personal computer standards, but is capable of radiation tolerance required on the MESSENGER mission. For data storage, the spacecraft carries two solid-state recorders (one backup) able to store up to one gigabyte each. Its main processor collects, compresses, and stores on the recorder images and other data from MESSENGER's instruments, which can then be sent back to Earth.

Scientific results



An image of part of the previously unseen side of the planet

MESSENGER performed its first Mercury flyby successfully on 14 January 2008, and its second flyby on 6 October 2008, taking pictures with both the wide angle and narrow angle cameras as well as using some of its other sensors. Preliminary image results from this first pass can be viewed at [JHUAPL's MESSENGER Science Photos page](#).

On July 3, 2008, MESSENGER team member Thomas Zurbuchen announced that the probe discovered large amounts of water present in Mercury's exosphere. "Nobody expected that. I don't know a single person that did. We were astonished, just astonished", Zurbuchen stated.

MESSENGER also provided visual evidence of volcanic activity on the surface of Mercury as well as evidence for a liquid planetary core.

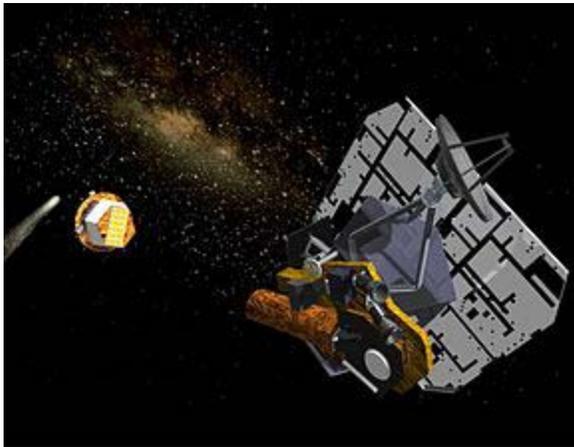
MESSENGER performed its third and last Mercury flyby on September 29, 2009 with the spacecraft coming within 142 mi (229 km) of the planet's surface. The inbound portion of the fly-by seems to have gone as planned, however sometime during the closest approach the spacecraft entered safe mode. Although this had no effect on the trajectory necessary for later orbit insertion it may have resulted in the loss of science data and images that were planned for the outbound leg of the fly-by. The spacecraft had fully recovered by about 7 hours later.

Chapter- 5

Space and Solar System Exploration in 2005

Deep Impact (spacecraft)

Deep Impact



Artist's conception of the *Deep Impact* space probe after impactor separation.

Operator	NASA / JPL
Major contractors	Ball Aerospace, JPL
Mission type	Flyby / Impactor
Flyby of	Tempel 1, Hartley 2
Launch date	2005-01-12 18:47:08 UTC (6 years and 2 days ago)
Launch vehicle	Delta II-7925
Launch site	Space Launch Complex 17B

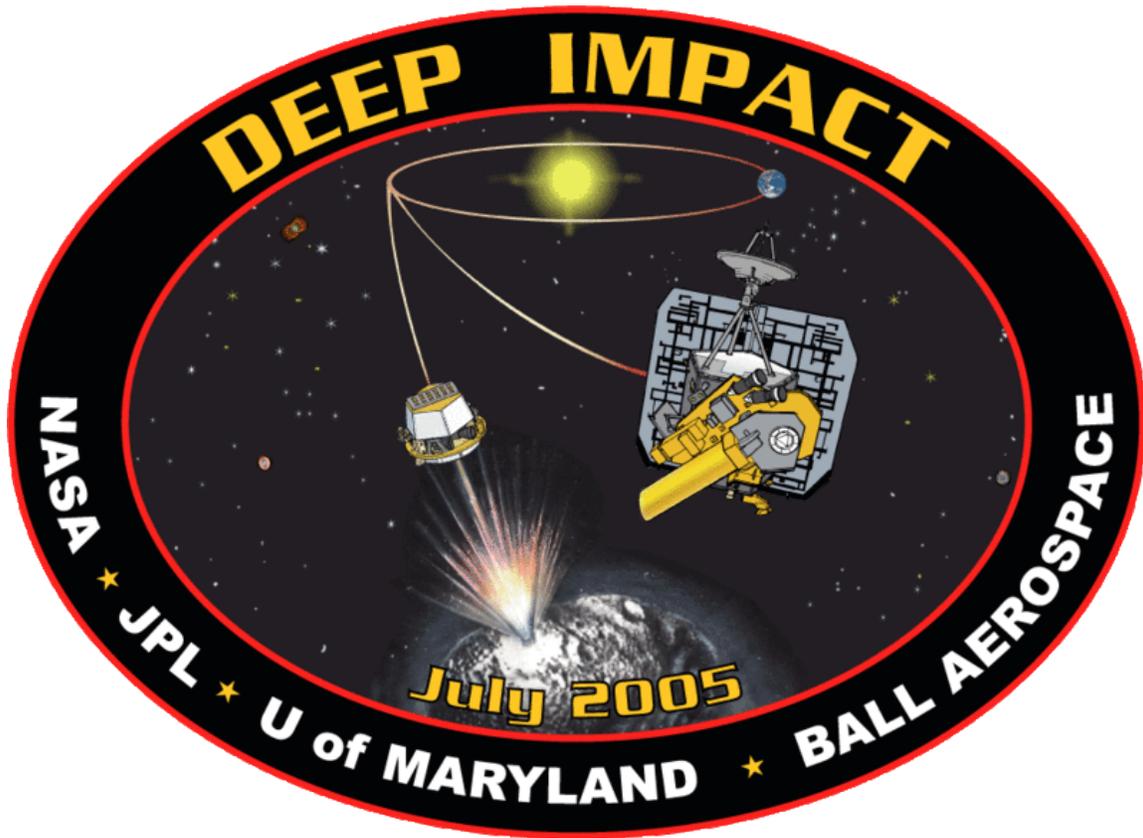
	Cape Canaveral Air Force Station
	In Progress (EPOXI)
	(5 years, 5 months, and 23 days elapsed)
Mission duration	Tempel 1 flyby (completed 2005-07-04)
	Hartley 2 flyby (completed 2010-11-25)
COSPAR ID	2005-001A
Mass	650 kg (1,433 lb)
	370 kg (816 lb) Impactor
Power	620 W (Solar array / NiH2 battery)

Deep Impact is a NASA space probe launched on January 12, 2005. It was designed to study the composition of the comet interior of 9P/Tempel, by releasing an impactor into the comet. At 5:52 UTC on July 4, 2005, the impactor successfully collided with the comet's nucleus. The impact excavated debris from the interior of the nucleus, allowing photographs of the impact crater. The photographs showed the comet to be more dusty and less icy than had been expected. The impact generated a large and bright dust cloud, which unexpectedly obscured the view of the impact crater.

Previous space missions to comets, such as *Giotto* and *Stardust*, were fly-by missions. These missions were only able to photograph and examine the surfaces of cometary nuclei from a distance. The *Deep Impact* mission was the first to eject material from a comet's surface, and the mission garnered large publicity from the media, international scientists, and amateur astronomers.

Upon the completion of its primary mission proposals were made to further utilize the spacecraft. Consequently, *Deep Impact* flew by Earth on December 31, 2007 on its way to an extended mission, designated EPOXI, with a dual purpose to study extrasolar planets and comet Hartley 2.

Scientific goals

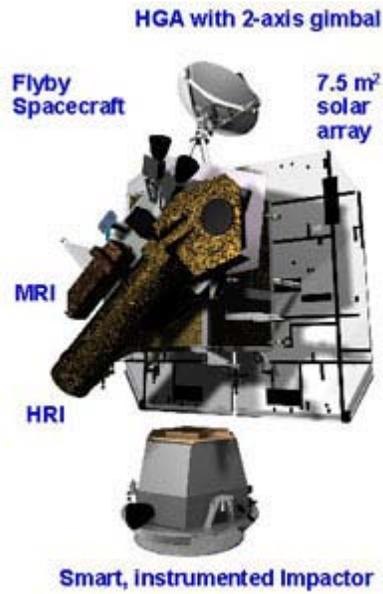


Deep Impact mission patch

The *Deep Impact* mission was planned to help answer fundamental questions about comets, which included what makes up the composition of the comet's nucleus, what depth the crater would reach from the impact, and where the comet originated in its formation. By observing the composition of the comet, astronomers hoped to determine how comets form based on the differences between the interior and exterior makeup of the comet. Observations of the impact and its aftermath would allow astronomers to attempt to determine the answers to these questions.

The mission's Principal Investigator was Michael A'Hearn, an astronomer at the University of Maryland. He led the science team, which included members from Cornell University, University of Maryland, University of Arizona, Brown University, Belton Space Exploration Initiatives, JPL, University of Hawaii, SAIC, Ball Aerospace, and Max-Planck-Institut für extraterrestrische Physik.

Spacecraft design and instrumentation



Spacecraft overview



Cameras of the flyby spacecraft, HRI at right, MRI at left

The spacecraft consists of two main sections, the 370-kg (815-lb) copper-core "Smart Impactor" that impacted the comet, and the "Flyby" section, which imaged the comet from a safe distance during the encounter with Tempel 1.

The Flyby spacecraft is about 3.2 meters (10.5 ft) long, 1.7 meters (5.6 ft) wide and 2.3 meters (7.5 ft) high. It includes two solar panels, a debris shield, and several science instruments for imaging, infrared spectroscopy, and optical navigation to its destination near the comet. The spacecraft also carried two cameras, the High Resolution Imager (HRI), and the Medium Resolution Imager (MRI). The HRI is an imaging device that combines a visible-light camera with a filter wheel, and an imaging infrared spectrometer called the "Spectral Imaging Module" or SIM that operates on a spectral band from 1.05 to 4.8 micrometres. It has been optimized for observing the comet's nucleus. The MRI is the backup device, and was used primarily for navigation during the final 10-day approach. It also has a filter wheel, with a slightly different set of filters.

The Impactor section of the spacecraft contains an instrument that is optically identical to the MRI, called the Impactor Targeting Sensor (ITS), but without the filter wheel. Its dual purpose was to sense the Impactor's trajectory, which could then be adjusted up to four times between release and impact, and to image the comet from close range. As the Impactor neared the comet's surface, this camera took high-resolution pictures of the nucleus (as good as 0.2 meters (0.7 ft) per pixel) that were transmitted in real-time to the Flyby spacecraft before it and the Impactor were destroyed. The final image taken by the impactor was snapped only 3.7 seconds before impact.

The impactor's payload, dubbed the "Cratering Mass", was 100% copper (impactor 49% copper by mass) to reduce debris interfering with scientific measurements of the impact. Since copper was not expected to be found on a comet, scientists could eliminate copper from the spectrometer reading. Instead of using explosives, it was also cheaper to use copper as the payload.

The name of the mission is shared with the 1998 *Deep Impact* film, in which a comet strikes the Earth. This is coincidental, however, as the scientists behind the mission and the creators of the film devised the name independently of each other at around the same time.

Mission profile



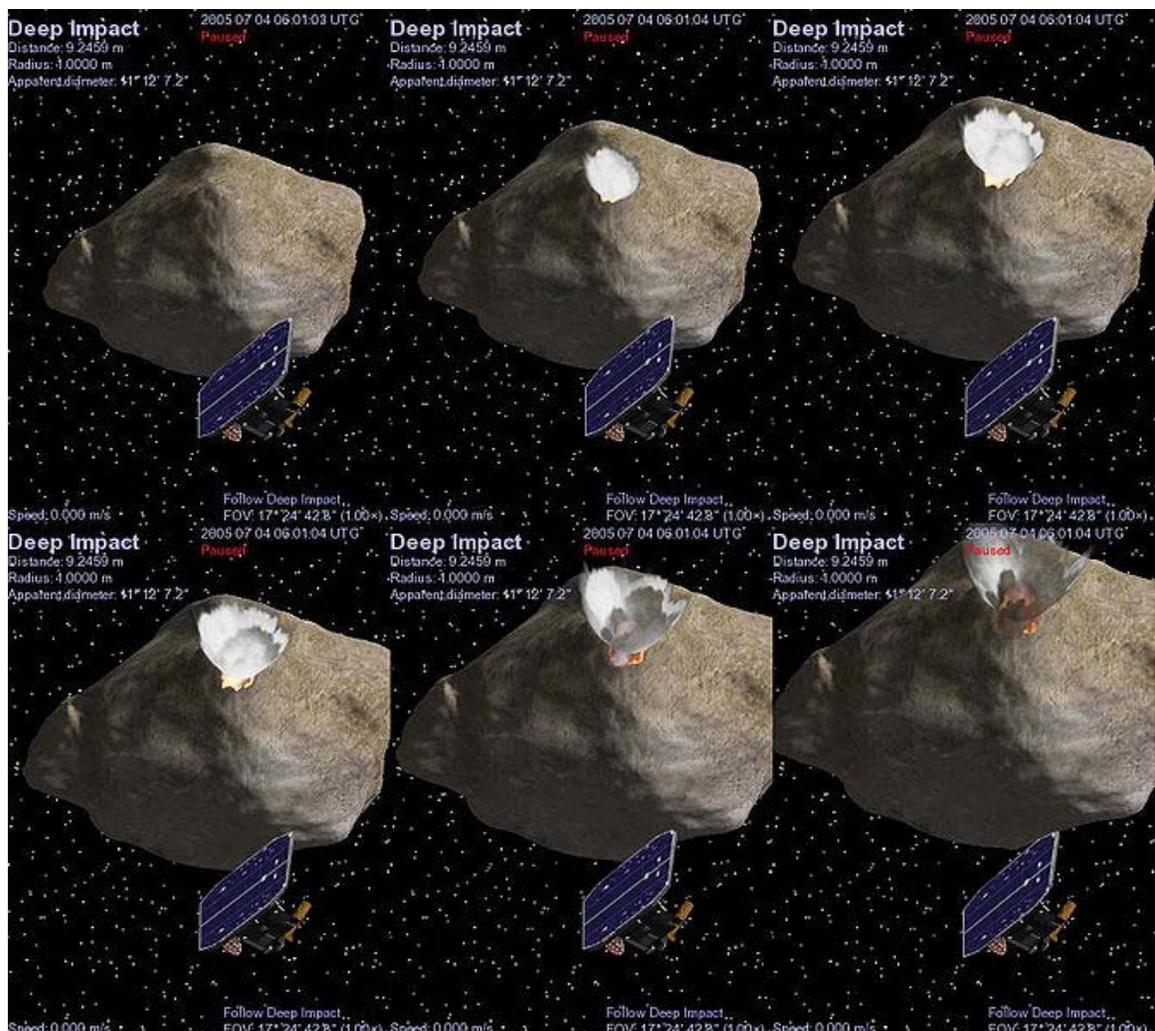
Deep Impact about to be launched with a Delta II rocket

Following its launch on January 12, 2005, the *Deep Impact* spacecraft traveled 429 million kilometers (267 million mi) in 174 days to reach comet 9P/Tempel at a cruising speed of 28.6 km/s (103,000 km/h or 64,000 mph). Once the spacecraft reached the vicinity of the comet on July 3, 2005, it separated into two portions, an impactor and a flyby probe. The impactor used its thrusters to move into the path of the comet, impacting 24 hours later at a relative speed of 10.3 km/s (37,000 km/h or 23,000 mph). The impactor, a 370-kilogram (820-pound) copper projectile, delivered 1.96×10^{10} joules of kinetic energy—the equivalent of 4.7 tons of TNT. Scientists believed that the energy of the high-velocity collision would be sufficient to excavate a crater up to 100 m (328 ft) wide (larger than the bowl of the Roman Colosseum). The size of the crater was still not known one year after the impact.

Just minutes after the impact, the flyby probe passed by the nucleus at a close distance of 500 km (310 mi), taking pictures of the crater position, the ejecta plume, and the entire cometary nucleus. The entire event was photographed by Earth-based telescopes and orbital observatories, including the Hubble, Chandra, Spitzer, and XMM-Newton. The impact was also observed by cameras and spectroscopes on board Europe's *Rosetta* spacecraft, which was about 80 million km (50 million mi) from the comet at the time of impact. *Rosetta* determined the composition of the gas and dust cloud that was kicked up by the impact.

Mission events

Before launch



Simulation: The collision of comet 9P/Tempel and the *Deep Impact* impactor, simulated by Celestia software using pre-impact information. The sun and the earth are on the right side. Note: The Deep Impact itself faces the wrong direction. The solar array should face the sun and the high-gain antenna should point to the earth.

A comet-impact mission was first proposed to NASA in 1996, but at the time, NASA engineers were skeptical that the target could be hit. In 1999, a revised and technologically upgraded mission proposal, dubbed *Deep Impact*, was accepted and funded as part of NASA's Discovery Program of low-cost spacecraft. The two spacecraft (Impactor and Flyby) and the three main instruments were built and integrated by Ball Aerospace & Technologies Corp. in Boulder, Colorado. Developing the software for the spacecraft took 18 months and the application code consisted of 20,000 lines and 19 different application threads. The total cost of developing the spacecraft and completing its mission reached \$330 million.

Launch and commissioning phase

The probe was originally scheduled for launch on December 30, 2004, but NASA officials delayed its launch, in order to allow more time for testing the software. It was successfully launched from Cape Canaveral on January 12, 2005 at 1:47 p.m. EST (1847 UTC) by a Delta 2 rocket.

Deep Impact's state of health was uncertain during the first day after launch. Shortly after entering orbit around the Sun and deploying its solar panels, the probe switched itself to safe mode. The cause of the problem was simply an incorrect temperature limit in the fault protection logic for the spacecraft's RCS thruster catalyst beds. The spacecraft's thrusters were used to detumble the spacecraft following third stage separation. NASA subsequently announced that the probe was out of safe mode and healthy.

On February 11, *Deep Impact's* rockets were fired as planned to correct the spacecraft's course. This correction was so precise that the next planned maneuver for March 31 was canceled. The "commissioning phase" verified that all instruments were activated and checked out. During these tests it was found that the HRI images were not in focus after it underwent a bake-out period. After mission members investigated the problem, on June 9, it was announced that by using image processing software and the mathematical technique of deconvolution, the HRI images could be corrected to restore much of the resolution anticipated.

Cruise phase



Comet 9P/Tempel imaged on April 25 by the Deep Impact spacecraft

The "cruise phase" began on March 25, immediately after the commissioning phase was completed. This phase continued until about 60 days before the encounter with comet 9P/Tempel. On April 25 the probe acquired the first image of its target at a distance of 64 million km (40 million miles).

On May 4 the spacecraft executed its second trajectory correction maneuver. Burning its rocket engine for 95 seconds, the spacecraft speed was changed by 18.2 km/h (11.3 mph). Rick Grammier, the project manager for the mission at NASA's Jet Propulsion Laboratory, reacted to the maneuver stating that "spacecraft performance has been

excellent, and this burn was no different...it was a textbook maneuver that placed us right on the money."

Approach phase

The approach phase extended from 60 days before encounter (May 5) until five days before encounter. Sixty days out was the earliest time that the *Deep Impact* spacecraft was expected to detect the comet with its MRI camera. In fact, the comet was spotted ahead of schedule, 69 days before impact. This milestone marks the beginning of an intensive period of observations to refine knowledge of the comet's orbit and study the comet's rotation, activity, and dust environment.

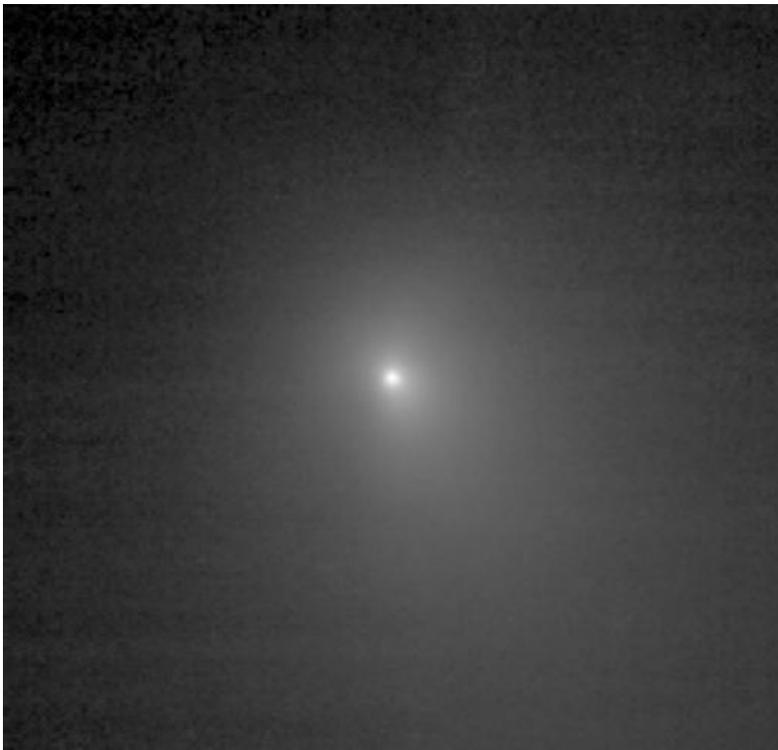
On June 14 and June 22, Deep Impact observed two outbursts of activity from the comet, the latter being six times larger than the former. The spacecraft studied the images of various distant stars to determine its current trajectory and position. Don Yeomans, a mission co-investigator for JPL pointed out that "it takes 7½ minutes for the signal to get back to Earth, so you cannot joystick this thing. You have to rely on the fact that the Impactor is a smart spacecraft as is the Flyby spacecraft. So you have to build in the intelligence ahead of time and let it do its thing." On June 23, the first of the two final trajectory correct maneuvers (targeting maneuver) was successfully executed. A 6 m/s (13.4 mph) velocity change was needed to adjust the flight path towards the comet and target the impactor at a window in space about 100 kilometers (62 mi) wide.



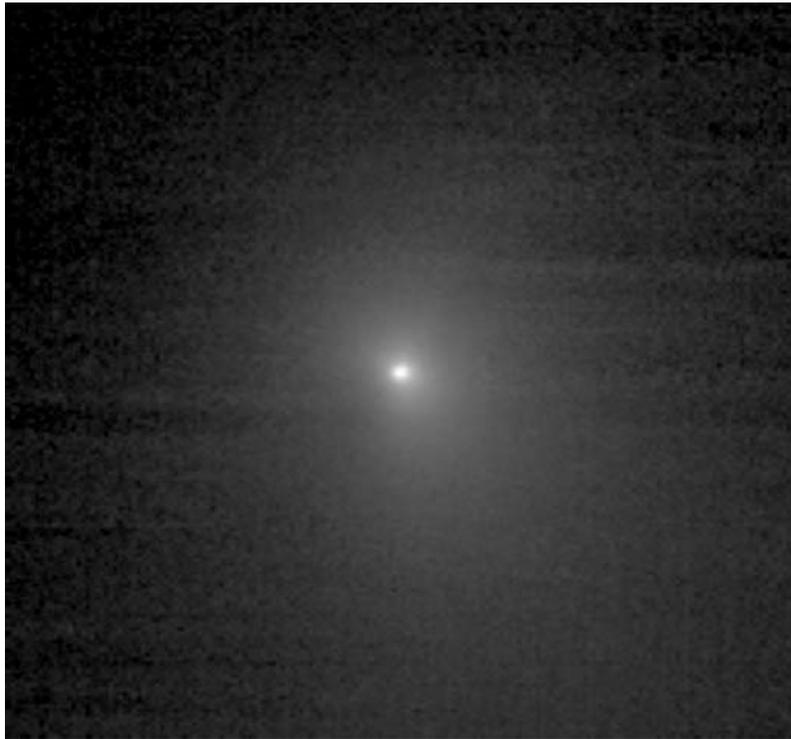
May 30, 2005, 35 days from impact



June 15, 19 days from impact

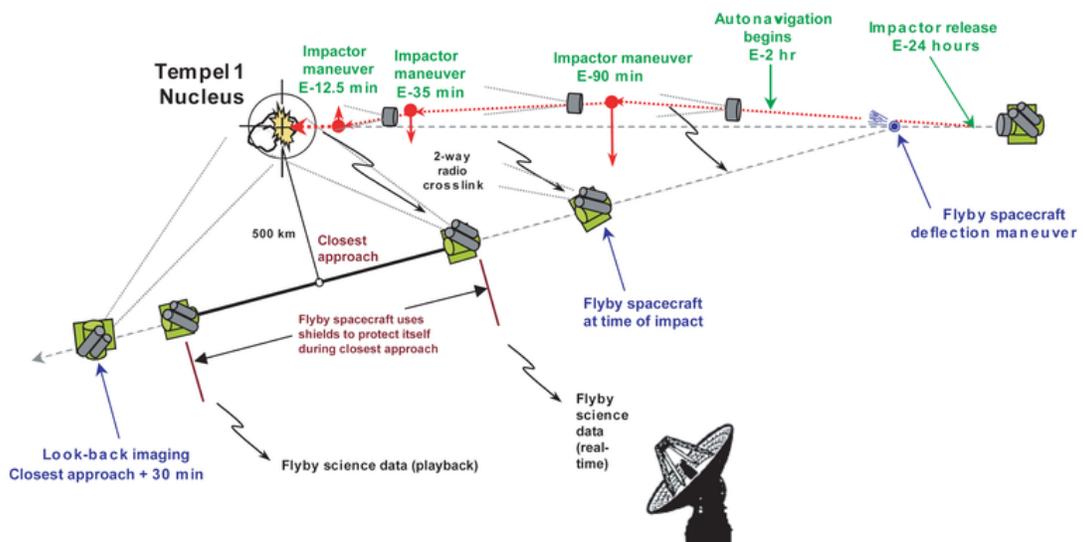


June 21, 13 days from impact



June 27, 7 days from impact, near end of approach phase

Impact phase



Deep Impact comet encounter sequence

Impact phase began nominally on June 29, five days before impact. The impactor successfully separated from the flyby spacecraft at 6:00 (6:07 Ground UTC) July 3 UTC. The first images from the instrumented Impactor were seen two hours after separation.

The flyby spacecraft performed one of two divert maneuvers to avoid damage. A 14-minute burn was executed which slowed down the spacecraft. It was also reported that the communication link between the flyby and the impactor was functioning as expected. The impactor spacecraft executed three correction maneuvers in the final two hours before impact.

The impactor was maneuvered to plant itself in front of the comet, so that 9P/Tempel would collide with it. Impact occurred at 05:45 UTC (05:52 Ground UTC, +/- up to three minutes, one-way light time = 7m 26s) on the morning of July 4, within one second of the expected time for impact.

The impactor returned images as late as three seconds before impact. Most of the data captured was stored on board the flyby spacecraft, which radioed approximately 4,500 images from the HRI, MRI, and ITS cameras to earth over the next few days. The energy from the collision was similar in size to exploding five tons of dynamite and the comet shone six times brighter than normal.

Impact Phase Timeline (NASA)

Results



Mission team members celebrate after the impact with the comet

Mission control did not become aware of the impactor's success until five minutes later at 0157 ET. Once news of a successful impact had taken place, the mission control team members applauded and hugged each other. Don Yeomans confirmed the results for the press, "We hit it just exactly where we wanted to" and JPL Director Charles Elachi stated "The success exceeded our expectations."

In the post-impact briefing at 0100 Pacific Daylight Time (08:00 UTC) on July 4, 2005, the first processed images revealed existing craters on the comet. NASA scientists stated they could not see the new crater that had formed from the impactor, but it was later discovered to be about 100 meters (328 ft) wide and up to 30 meters (98 ft) deep. Lucy McFadden, one of the co-investigators of the impact, stated "We didn't expect the success of one part of the mission [bright dust cloud] to affect a second part [seeing the resultant crater]. But that is part of the fun of science, to meet with the unexpected." Analysis of data from the Swift X-ray telescope showed that the comet continued outgassing from the impact for 13 days, with a peak five days after impact. A total of 5 million kilograms (11 million pounds) of water and between 10 and 25 million kilograms (22 and 55 million pounds) of dust were lost from the impact.

Initial results were surprising as the material excavated by the impact contained more dust and less ice than had been expected. The only models of cometary structure astronomers could positively rule out were the very porous models which had comets as loose aggregates of material. In addition, the material was finer than expected; scientists compared it to talcum powder rather than sand. Other materials found while studying the impact included clays, carbonates, sodium, and crystalline silicates which were found by studying the spectroscopy of the impact. Clays and carbonates usually require liquid water to form and sodium is rare in space. Observations also revealed that the comet was about 75% empty space, and one astronomer compared the outer layers of the comet to the same makeup of a snow bank. Astronomers have expressed interest in more missions to different comets to determine if they share similar compositions or if there are different materials found deeper within comets that were produced at the time of the solar system's formation.

Astronomers determined that the comet had possibly formed in the Uranus and Neptune Oort cloud region of the solar system. Based on its interior chemistry, astronomers were able to determine that a comet which forms farther from the Sun will have greater amounts of ices with low freezing temperatures, such as ethane, which was present in 9P/Tempel. If comets have similar compositions as Tempel, astronomers believe they could have formed in the same region.

Public interest

Media coverage



This image was circulated widely in the media

The impact was a substantial news event reported and discussed online, in print, and on television. There was a genuine suspense because experts held widely differing opinions over the result of the impact. Various experts debated whether the impactor would go straight through the comet and out the other side, would create an impact crater, would open up a hole in the interior of the comet, and other theories. However, twenty-four hours before impact, the flight team at JPL began privately expressing a high level of confidence that, barring any unforeseen technical glitches, the spacecraft would intercept

9P/Tempel. One senior personnel member stated "All we can do now is sit back and wait. Everything we can technically do to ensure impact has been done." In the final minutes as the impactor hit the comet, more than 10,000 people watched the collision on a giant movie screen at Hawaii's Waikiki Beach.

Experts came up with a range of soundbites to summarize the mission to the public. Iwan Williams of Queen Mary, University of London, said "It was like a mosquito hitting a 747. What we've found is that the mosquito didn't splat on the surface; it is actually gone through the windscreen."

One day after the impact Marina Bay, a Russian astrologer, sued NASA for \$300 million for the impact which "ruin[ed] the natural balance of forces in the universe." Her lawyer asked the public to volunteer to help in the claim by declaring "The impact changed the magnetic properties of the comet, and this could have affected mobile telephony here on Earth. If your phone went down this morning, ask yourself Why? and then get in touch with us." On August 9, 2005 the Presnensky Court of Moscow ruled against Bay, although she did attempt to appeal the result. One Russian physicist said that the impact had no effect on Earth and "the change to the orbit of the comet after the collision was only about 10 cm (3.9 in)."

Send Your Name To A Comet!



The CD containing the 625,000 names is added to the Impactor

The mission was notable for one of its promotional activities, "Send Your Name To A Comet!". Visitors to the Jet Propulsion Laboratory's website were invited to submit their name between May 2003 and January 2004, and the names gathered—some 625,000 in all—were then burnt onto a mini-CD, which was attached to the impactor. Dr. Don Yeomans, a member of the spacecraft's scientific team, stated "this is an opportunity to become part of an extraordinary space mission ... when the craft is launched in December 2004, yours and the names of your loved-ones can hitch along for the ride and be part of what may be the best space fireworks show in history." The idea was credited with driving interest in the mission.

Reaction from China

Chinese researchers used the *Deep Impact* mission as an opportunity to highlight the efficiency of American science because public support ensured the possibility of funding long-term research. By contrast, "in China, the public usually has no idea what our scientists are doing, and limited funding for the promotion of science weakens people's enthusiasm for research."

Two days after the U.S. mission succeeded in having a probe collide with a comet, China revealed a plan for what it called a "more clever" version of the mission: landing a probe on a small comet or asteroid to push it off course. China will begin the mission after sending a probe to the Moon.

Contributions from amateur astronomers

	<p style="text-align: center;">DEEP IMPACT MISSION First Look Inside a Comet</p> <p style="text-align: center;">Participation Certificate</p> <p style="text-align: center;"><i>Presented to</i></p> <p style="text-align: center;">Mathias Rex</p> <p style="text-align: center;">On May 13, 2003</p> <p>Thank you for your participation in the Deep Impact Discovery Mission to Comet Tempel 1. A compact disc bearing your name will be mounted on the impactor spacecraft that will collide with Tempel 1 making this the first mission ever to look deep inside a comet.</p> <p>You are now part of the future discovery of clues about the beginning of our solar system as your name makes a Deep Impact!</p> <p><i>Edward J. Weiler</i> Dr. Edward J. Weiler Associate Administrator NASA Office of Space Science</p> <p><i>Michael F. A'Hearn</i> Michael F. A'Hearn Principal Investigator Deep Impact Mission University of Maryland</p> <p style="text-align: center;"></p> <p style="text-align: center;">Certificate No. 94365</p>
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Deep Impact participation certificate of Maciej Szczepańczyk

Since observing time on large, professional telescopes such as Keck or Hubble is always scarce, the *Deep Impact* scientists called upon "advanced amateur, student, and professional astronomers" to use small telescopes to make long-term observations of the target comet before and after impact. The purpose of these observations was to look for "volatile outgassing, dust coma development and dust production rates, dust tail development, and jet activity and outbursts." By mid-2007, amateur astronomers had submitted over a thousand CCD images of the comet.

One notable amateur observation was by students from schools in Hawaii, working with US and UK scientists, who during the press conference took live images using the Faulkes Automatic Telescope in Hawaii (the students operated the telescope over the

Internet) and were one of the first groups to get images of the impact. One amateur astronomer reported seeing a structureless bright cloud around the comet, and an estimated magnitude 2 increase in brightness after the impact. Another amateur published a map of the crash area from NASA images.

Musical tribute

The *Deep Impact* mission coincided with celebrations in the Los Angeles area marking the 50th anniversary of "Rock Around the Clock" by Bill Haley and His Comets becoming the first rock and roll single to reach No. 1 on the recording sales charts. Within twenty-four hours of the mission's success, a two-minute music video produced by Martin Lewis had been created using images of the impact itself combined with computer animation of the *Deep Impact* probe in flight, interspersed with footage of Bill Haley and His Comets performing in 1955 and the surviving original members of The Comets performing in March 2005. The video was posted to NASA's website for a couple of weeks afterwards.

On July 5, the surviving original members of The Comets (ranging in age from 71 to 84) performed a free concert for hundreds of employees of the Jet Propulsion Laboratory to help them celebrate the mission's success. This event received worldwide press attention. Later, in February 2006, the International Astronomical Union citation that officially named asteroid 79896 Billhaley included a reference to the JPL concert.

Extended mission

Deep Impact is now on an extended mission designated EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation) to visit other comets, after being put to sleep in 2005 upon completion of the Tempel 1 mission.

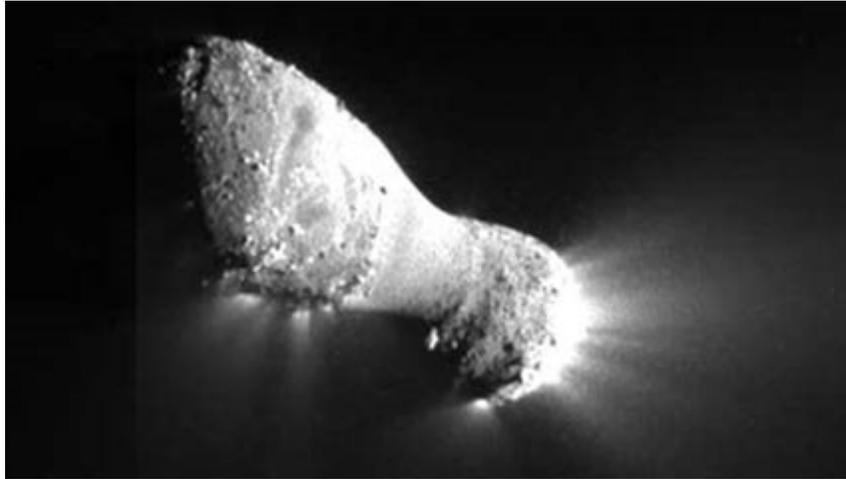
Flyby of Comet Boethin

Its first extended visit was to do a flyby of Comet Boethin, but with some complications. On July 21, 2005 *Deep Impact* executed a trajectory correction maneuver that allows the spacecraft to use Earth's gravity to begin a new mission in a path towards another comet.

The original plan was for a December 5, 2008 flyby of Comet Boethin, coming within 700 kilometers (435 miles) of the comet. Michael A'Hearn, the *Deep Impact* team leader, explained "We propose to direct the spacecraft for a flyby of Comet Boethin to investigate whether the results found at Comet Tempel 1 are unique or are also found on other comets." The \$40 million mission would provide about half of the information as the collision of Tempel 1 but at a fraction of the cost. *Deep Impact* would use its spectrometer to study the comet's surface composition and its telescope for viewing the surface features.

However, as the Earth gravity assist approached, astronomers were unable to locate Comet Boethin, which may have broken up into pieces too faint to be observed. Consequently, its orbit could not be calculated with sufficient precision to permit a flyby.

Flyby of Comet Hartley 2



Comet Hartley 2 on November 4, 2010

JPL team targeted *Deep Impact* toward Comet Hartley 2. However, this would require an extra two years of travel for *Deep Impact*. On May 28, 2010, a burn of 11.3 seconds was conducted, to enable the June 27 Earth fly-by to be optimized for the transit to Hartley 2 and fly-by on November 4. The velocity change was 0.1 metres per second (0.22 mph).

On November 4, the Deep Impact extended mission (EPOXI) returned images from comet Hartley 2. EPOXI came within 700 kilometers (430 mi) of the comet, returning detailed photographs of the "peanut" shaped cometary nucleus and several bright jets. The probe's medium-resolution instrument captured the photographs.

Mars Reconnaissance Orbiter

Mars Reconnaissance Orbiter



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

Operator	NASA / JPL Lockheed Martin Space Systems University of Arizona
Major contractors	Applied Physics Laboratory Italian Space Agency Malin Space Science Systems,
Mission type	Orbiter
Satellite of	Mars
Orbital insertion date	2006-03-10 21:24:00 UTC
Launch date	2005-08-12 11:43:00 UTC
Carrier rocket	Atlas V-401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	Primary mission: >2 years

elapsed: 5 years, 5 months, and 5 days

COSPAR ID	2005-029A
Mass	2,180 kilograms (4,800 lb) fueled
	1,031 kilograms (2,270 lb) dry
Power	1,000.0 W

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

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

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

Pre-launch

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

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

On October 3, 2001, NASA chose Lockheed Martin as the primary contractor for the spacecraft's fabrication. By the end of 2001 all of the mission's instruments were selected.

There were no major setbacks during MRO's construction, and the spacecraft was moved to John F. Kennedy Space Center on May 1, 2005 to prepare it for launch.

Mission objectives

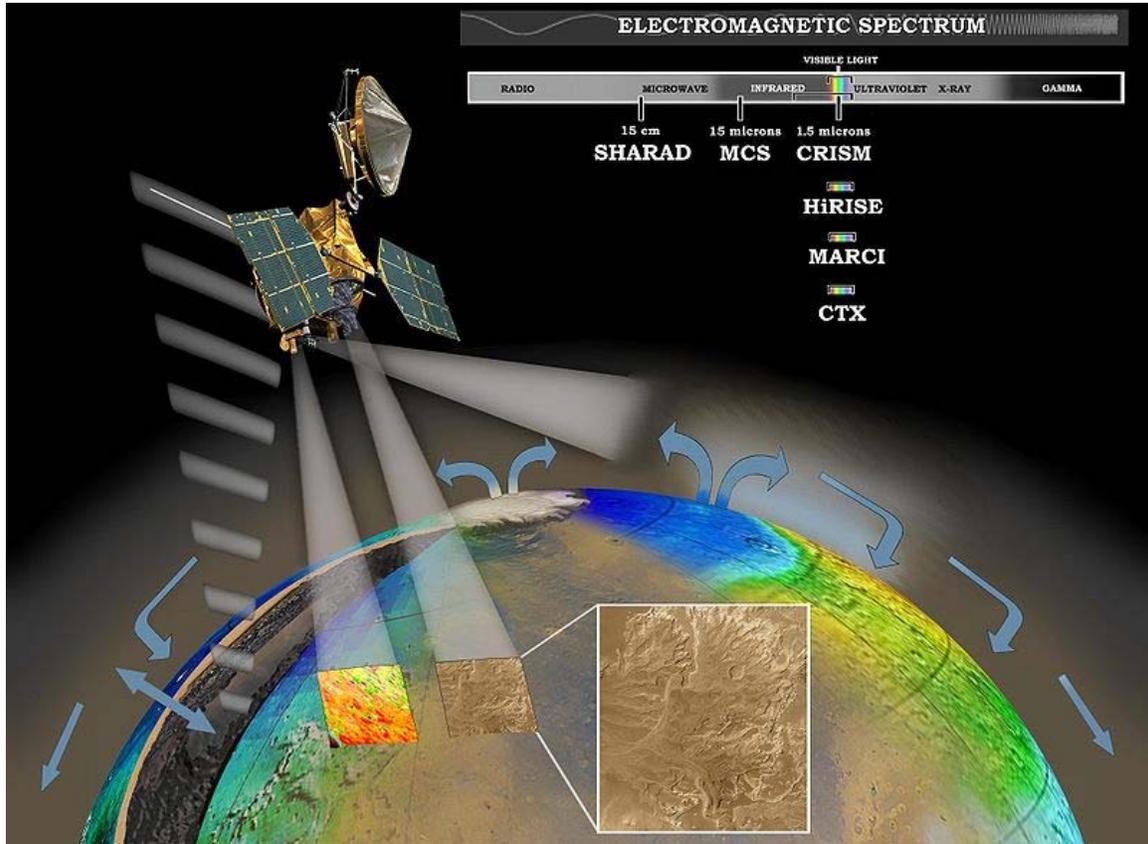


Diagram of instrumentation aboard MRO

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

MRO is using its on-board scientific equipment to study the Martian climate, weather, atmosphere, and geology, and to search for signs of water in the polar caps and underground. In addition, MRO is looking for the remains of the previously lost Mars Polar Lander and Beagle 2 spacecraft, and serves as the first step in setting up an internet

protocol network for the planets in our solar system. After its main science operations are completed, the probe's extended mission is to be the communication and navigation system for landers and rover probes.

Launch and orbital insertion

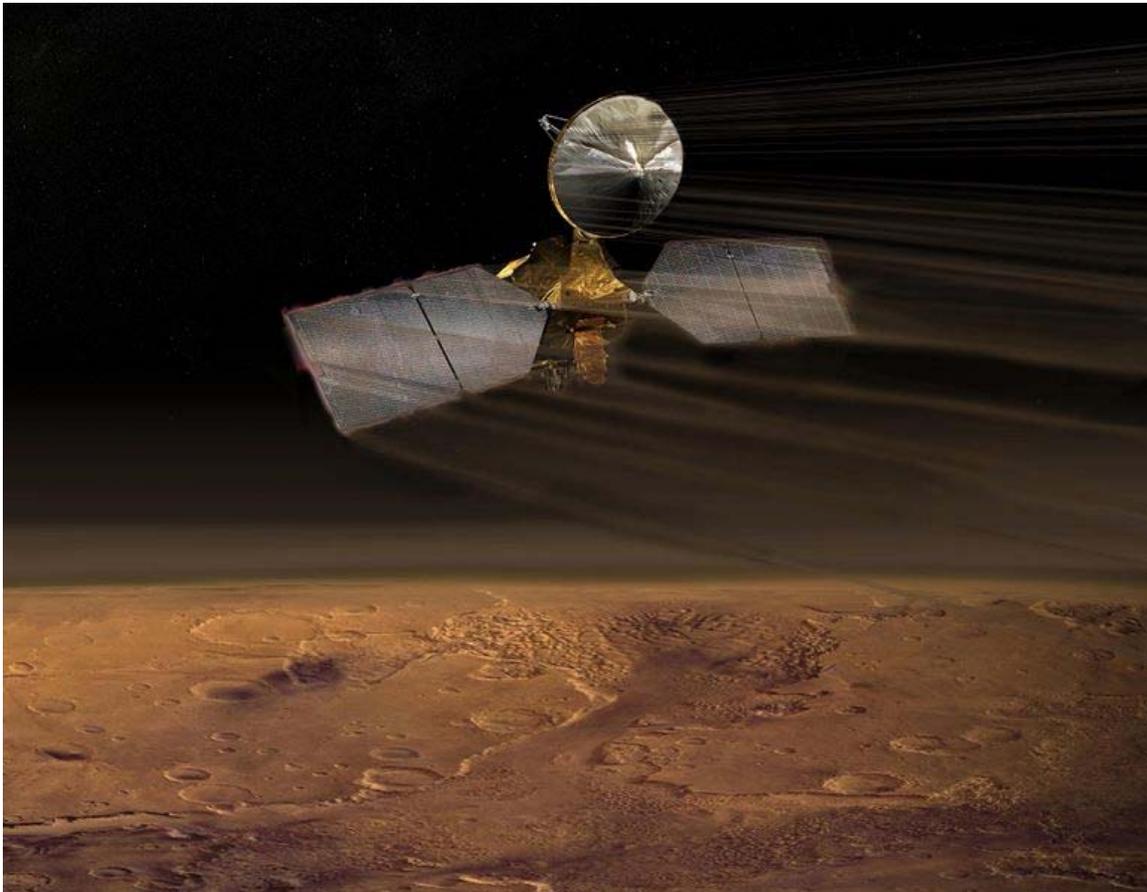


Launch of Atlas V carrying the Mars Reconnaissance Orbiter, 11:43:00 UTC August 12, 2005

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

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

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



Artwork of MRO aerobraking

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

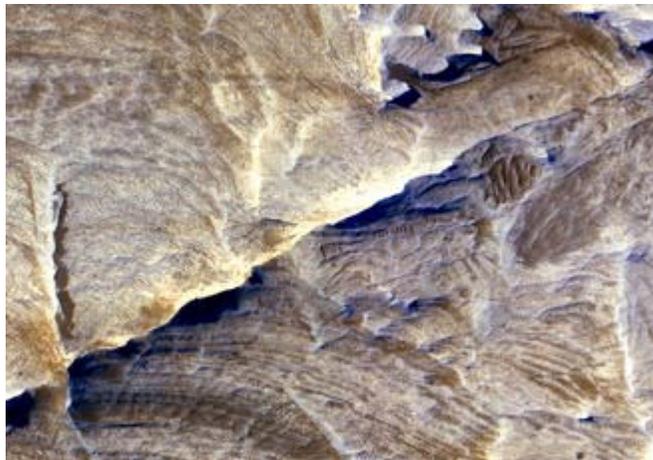
surface). The apoapsis – the point in the orbit farthest from Mars – was 47,972 km from the planet's center (44,500 km from its surface).

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

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

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

Events and discoveries



Tectonic fractures within the Candor Chasma region of Valles Marineris, Mars, retain ridge-like shapes as the surrounding bedrock erodes away. This points to past episodes of fluid alteration along the fractures and reveals clues into past fluid flow and geochemical conditions below the surface.

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

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

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

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

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

Instruments

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

HiRISE (camera)



HiRISE camera structure

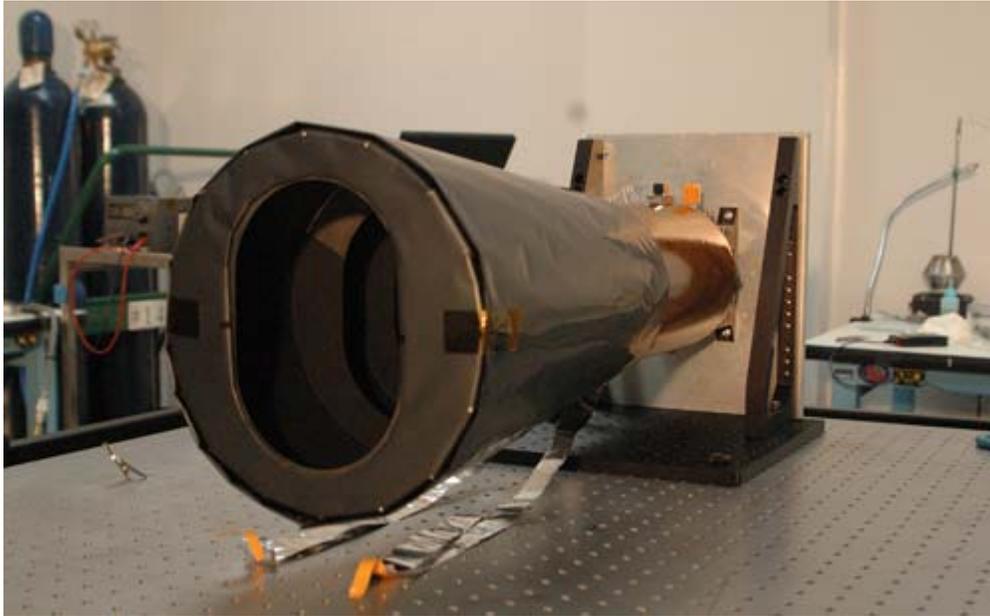
The High Resolution Imaging Science Experiment camera is a 0.5 m reflecting telescope, the largest ever carried on a deep space mission, and has a resolution of 1 microradian (μrad), or 0.3 m from an altitude of 300 km. In comparison, satellite images of Earth are generally available with a resolution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



HiRISE image of the 'face' at Cydonia Mesa

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

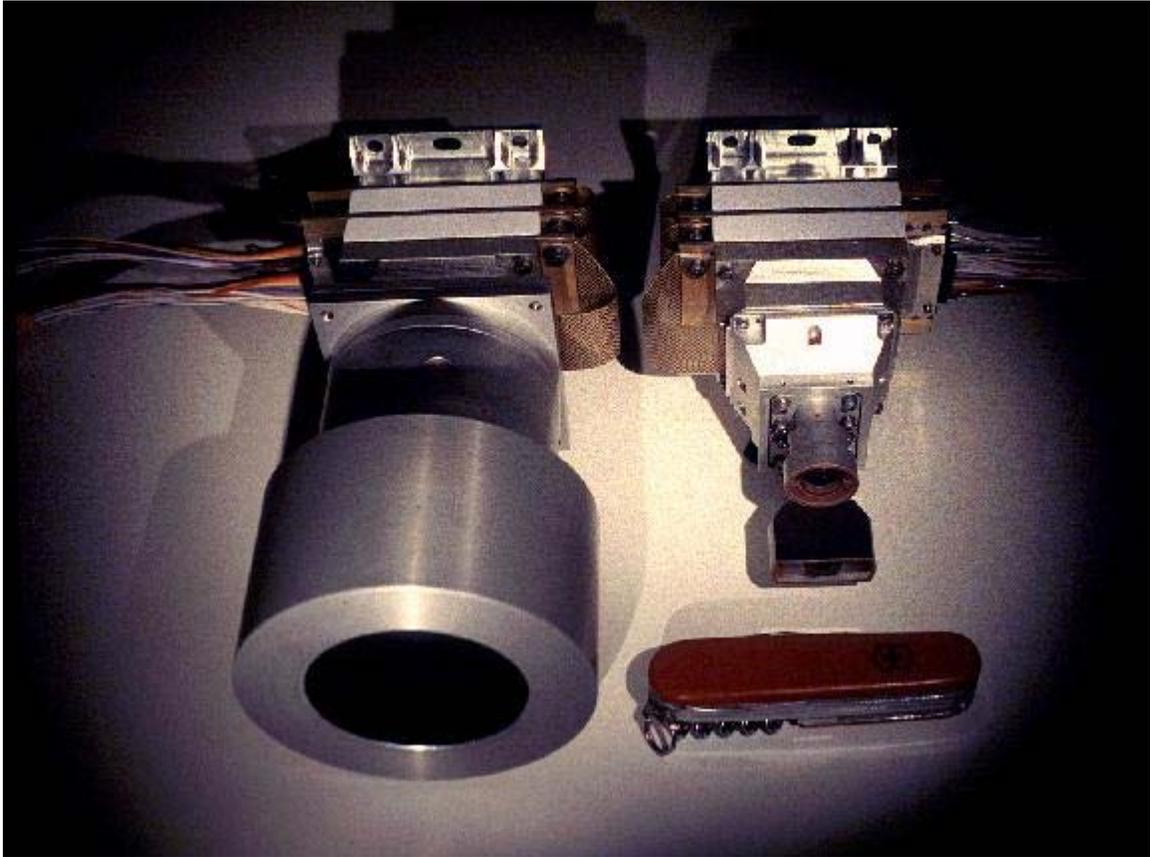
CTX (camera)



Context (CTX) Camera

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

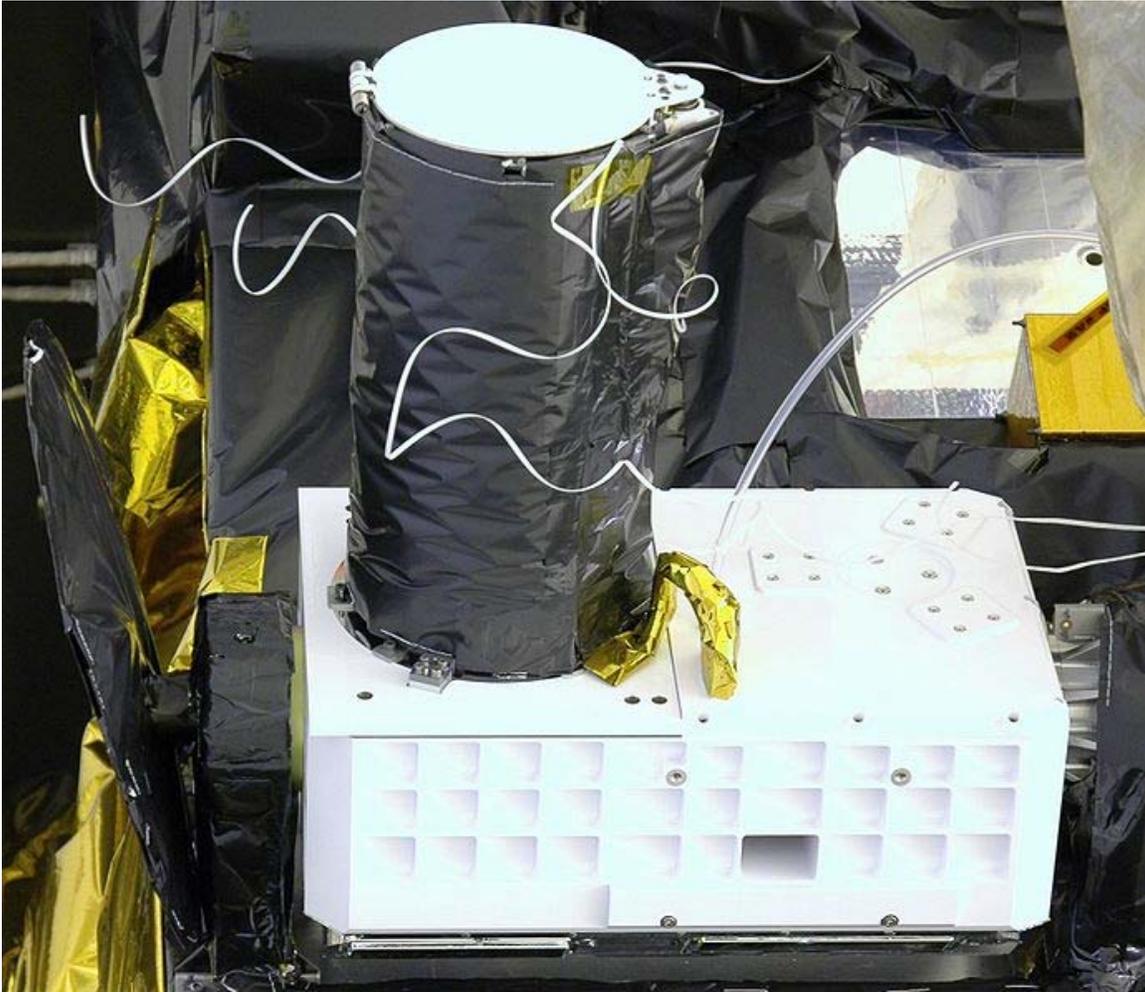
MARCI (camera)



Mars Color Imager

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

CRISM (spectrometer)



CRISM Instrument

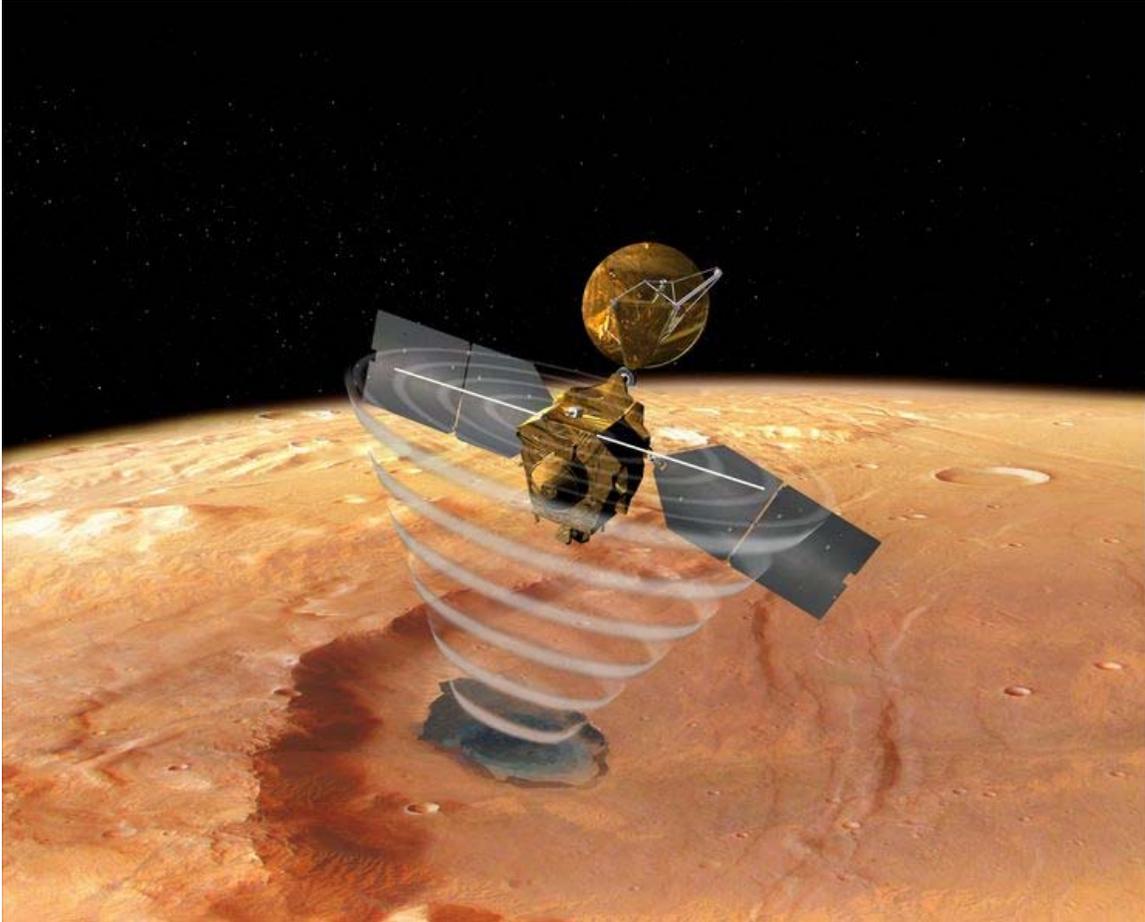
The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument is a visible and near infrared (VNIR) spectrometer that is used to produce detailed maps of the surface mineralogy of Mars. It operates from 370 to 3920 nm, measures the spectrum in 544 channels (each 6.55 nm wide), and has a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

MCS (spectrometer)

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

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

SHARAD (radar)



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

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

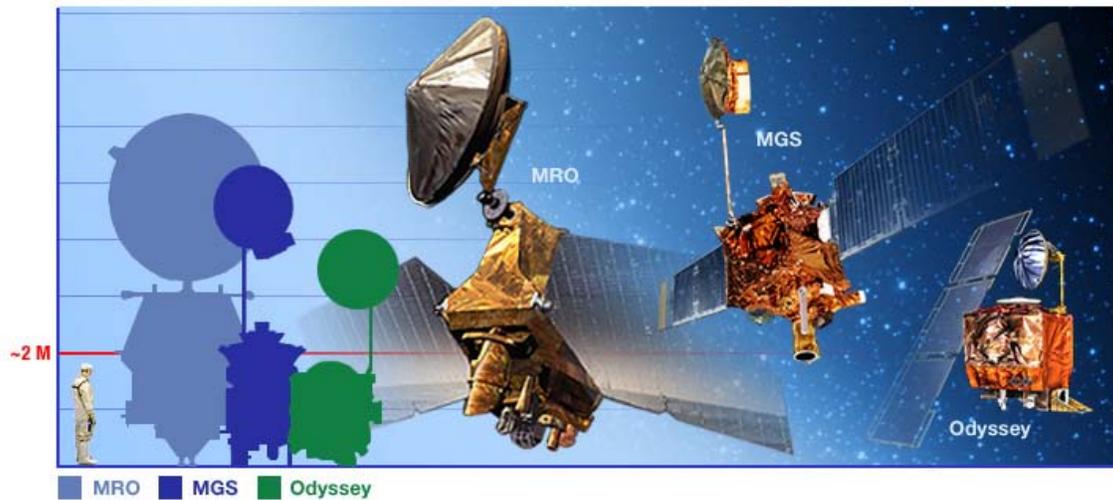
Engineering instruments

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

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

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

Engineering data



Size comparison of MRO with predecessors

Structure

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

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

Power systems



The Mars Reconnaissance Orbiter solar panel

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

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

Electronic systems

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

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

Attitude determination

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

Telecommunications system



MRO High Gain Antenna installation

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

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

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

Propulsion and attitude control



Data comparison chart

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

MRO has twenty rocket engine thrusters on board. Six large thrusters each produce 170 N (38 lbf) of thrust for a total of 1,020 N (230 lbf) meant mainly for orbital insertion.

These thrusters were originally designed for the Mars Surveyor 2001 Lander. Six medium thrusters each produce 22 N (5 lbf) of thrust for trajectory correction maneuvers and attitude control during orbit insertion. Finally, eight small thrusters each produce 0.9 N (0.2 lbf) of thrust for attitude control during normal operations.

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

Discoveries and photographs

Water ice in ice cap measured

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

Ice exposed in new craters



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

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

Lobate debris aprons



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

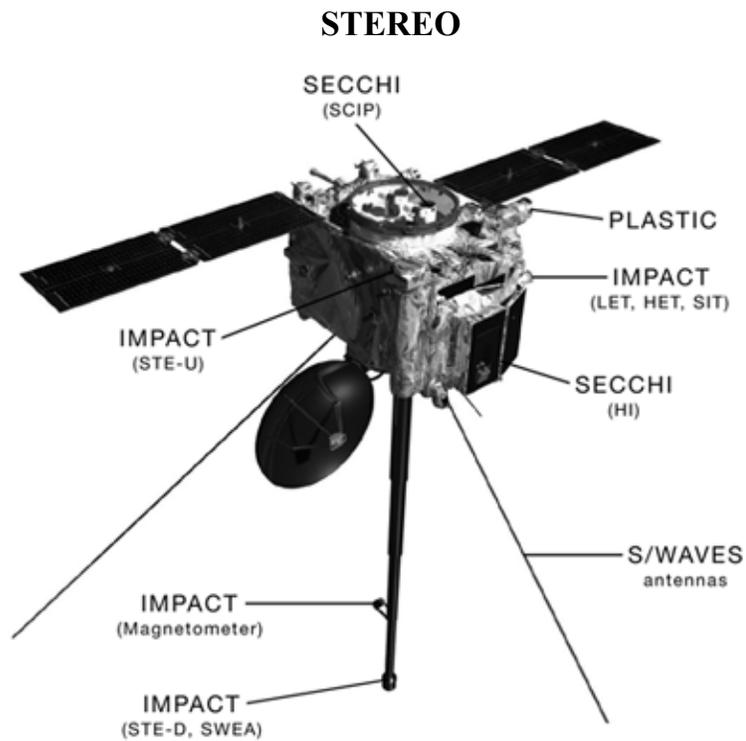
One of the most important discoveries made by the Mars Reconnaissance Orbiter was that features called Lobate Debris Aprons (LDA's) contain large amounts of water ice. Of

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

Chapter- 6

Space and Solar System Exploration in 2006

STEREO



One of two STEREO spacecraft

Operator	NASA
Major contractors	Johns Hopkins University Applied Physics Laboratory
Mission type	Orbiter

Satellite of	Sun
Launch date	2006-10-26, 00:52:00 UTC
Carrier rocket	Delta II 7925-10L
Launch site	Space Launch Complex 17-B Cape Canaveral Air Force Station
Mission duration	>3 years 4 years, 2 months, and 20 days
COSPAR ID	2006-047
Mass	620 kg
Power	475.0 W

Orbital elements

Orbital period	STEREO A: 346 days STEREO B: 388 days
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Instruments

Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI):

Main instruments	<ul style="list-style-type: none"> • Extreme UltraViolet Imager (EUVI) • Inner Coronagraph (COR1) • Outer Coronagraph (COR2) • Heliospheric Imager (HI) • Sungrazing Comets
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STEREO (Solar **TE**rrestrial **RE**lations **O**bservatory) is a solar observation mission. Two nearly identical spacecraft were launched into orbits that cause them to respectively pull further ahead of and fall gradually behind the Earth. This will enable stereoscopic imaging of the Sun and solar phenomena, such as coronal mass ejections.

Mission profile



Launch of the STEREO spacecraft atop a Delta II (7925-10L) rocket, 00:52 GMT on 26 October 2006

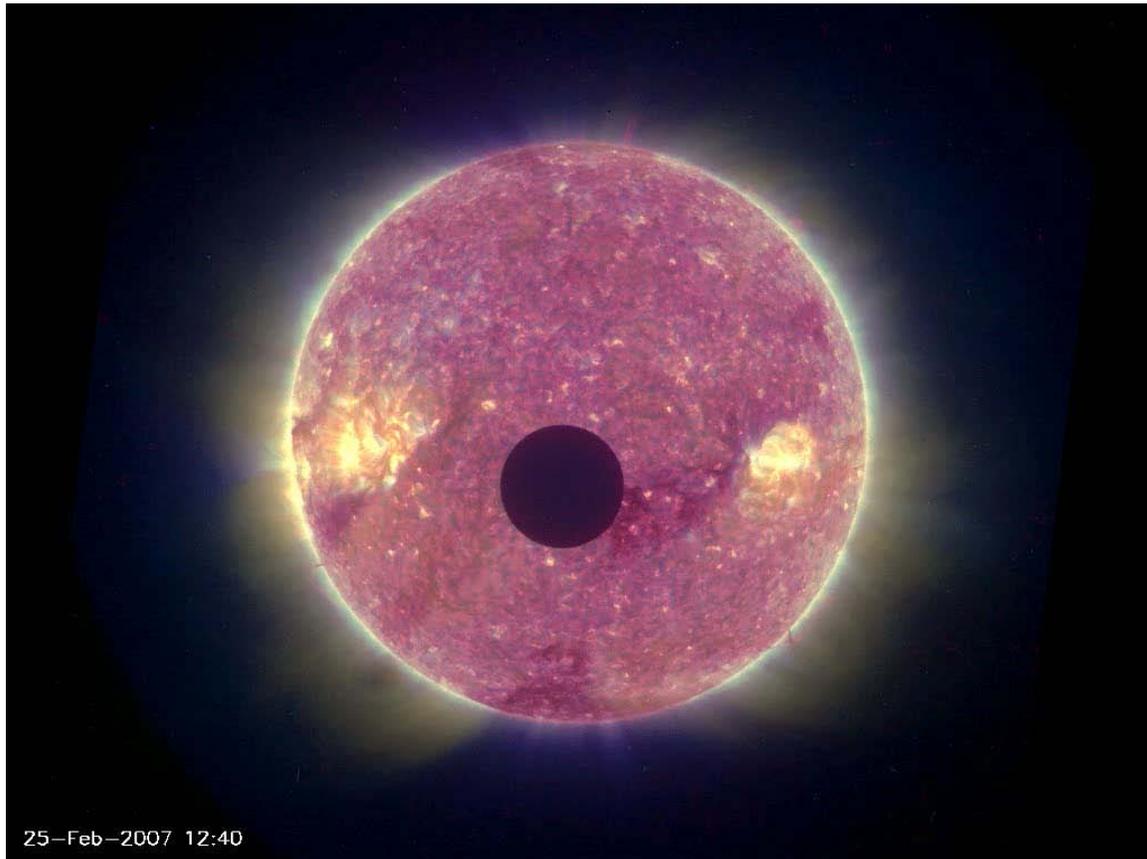
The two STEREO spacecraft were launched at 0052 UTC on October 26, 2006 from Launch Pad 17B at the Cape Canaveral Air Force Station in Florida on a Delta II 7925-10L launcher into highly elliptical geocentric orbits. The apogee reached the Moon's orbit. On December 15, 2006, on the fifth orbit, the pair swung by the Moon for a gravitational slingshot. Because the two spacecraft were in slightly different orbits, the "ahead" (A) spacecraft was ejected to a heliocentric orbit inside Earth's orbit while the "behind" (B) spacecraft remained temporarily in a high earth orbit. The B spacecraft

encountered the Moon again on the same orbital revolution on January 21, 2007, ejecting itself from earth orbit in the opposite direction from spacecraft A. Spacecraft B entered a heliocentric orbit outside the Earth's orbit. Spacecraft A will take 347 days to complete one revolution of the sun and Spacecraft B will take 387 days. The A spacecraft/sun/earth angle will increase at 21.650 deg/year. The B spacecraft/sun/earth angle will change - 21.999 degrees per year. Their current locations are shown here.

Because the A spacecraft is moving faster than B, they are separating from each other and A is orbiting closer to the sun than B. This means stereoscopic pairs of images will soon be impossible for human eyes to fuse, which is a STEREO paradox. as human brain can perceive three dimensional vision for the human eye separation angle, which is usually less than a few degrees, while STEREO spacecraft are separated up to 180 degrees as seen from the Sun. At the end of March 2007, the stereoscopic parallax was 1/50, but by June 2007 it was already 1/25. "Ideal" stereoscopic parallax is 1/30 and below 1/10 fusion is difficult even for experts. Already the east and west edges of the sun were becoming difficult, because one eye would see further around the sun than the other. The middle of the solar disc and up towards the poles will be fused stereoscopically after the edges become impossible. The A images, from the satellite closer to the sun, are bigger than B. Magnification must be corrected before stereoscopic fusion by human eyes is possible. Of course the mission does not depend on 3D vision to be useful and mathematical reduction of STEREO image data will continue.

Over time, the STEREO spacecraft will continue to separate from each other at a combined rate of approximately 44 degrees per year. There are no *final* positions for the spacecraft. They achieved 90 degrees separation on January 24, 2009, a condition known as quadrature. This is of interest because the mass ejections seen from the side on the limb by one spacecraft can potentially be observed by the *in situ* particle experiments of the other spacecraft. As they pass through Earth's Lagrangian points L₄ and L₅ (in late 2009), they will search for Lagrangian (trojan) asteroids. On February 6, 2011, the two spacecraft will be exactly 180 degrees apart from each other, allowing the entire Sun to be seen for the first time. Even as the angle increases, the addition of an Earth-based view, e.g. from the Solar Dynamics Observatory, will still provide full-Sun observations for several years. In 2015, contact will be lost for several months when the spacecraft pass behind the Sun. After this, they can continue to be operated after rolling by 180 degrees to point the high gain antenna at Earth. They will then start to approach Earth again, with closest approach sometime in 2023. They will not be recaptured into Earth orbit.

Science instrumentation



A lunar transit of the sun captured during calibration of Stereo B's Ultra Violet imaging cameras. The Moon appears much smaller than it does seen from Earth, because the spacecraft-Moon separation was several times greater than the Earth-Moon distance.

Each of the spacecraft carries cameras, particle experiments and radio detectors in four instrument packages:

- **Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)** - SECCHI has five cameras: an extreme ultraviolet imager (EUVI) and two white-light coronagraphs (collectively known as the Sun Centered Instrument Package or SCIP), which image the solar disk and the inner and outer corona, plus two heliospheric imagers (called the HI), which image the space between Sun and Earth. The purpose of SECCHI is to study the 3-D evolution of Coronal Mass Ejections through their full journey from the Sun's surface through the corona and interplanetary medium to their impact at Earth.
- **In-situ Measurements of Particles and CME Transients (IMPACT)** - IMPACT will study energetic particles, the three-dimensional distribution of solar wind electrons and interplanetary magnetic field.

- **PLAsma and SupraThermal Ion Composition (PLASTIC)** - PLASTIC will study the plasma characteristics of protons, alpha particles and heavy ions.
- **STEREO/WAVES (SWAVES)** - SWAVES is a radio burst tracker that will study radio disturbances traveling from the Sun to the orbit of Earth.

Spacecraft subsystems

- **Structure**

Launch weight including propellants was 1364 pounds (620 kg).

- **Propulsion and attitude control**

3-axis control

- **Attitude determination** - Each STEREO spacecraft has a primary and a backup Miniature Inertial Measurement Unit (MIMU), provided by Honeywell, which measure changes to the spacecraft attitude. Each MIMU is equipped with three ring laser gyroscopes to detect angular changes. Additional attitude information is provided by the Star Tracker and the SECCHI Guide Telescope.
- **Power**

475 Watts from solar panels.

- **Telecommunications**

Data downlink: 720 kilobits per second.

- **Flight computers**

STEREO's onboard computer systems are based on the Integrated Electronics Module (IEM), a device that combines core avionics in a single box. Each single-string spacecraft carries two 25 megahertz RAD6000 CPUs: one for Command/Data-handling, and one for Guidance-and-Control. Both are radiation hardened RAD6000 processors, based on IBM POWER CPUs (predecessor of the PowerPC chip found in older Macintoshes). The computers, slow by current personal computer standards, are typical for the radiation requirements needed on the STEREO mission.

- **Data handling**

For data storage, each spacecraft carries a solid state recorder able to store up to one gigabyte each. Its main processor collects and stores on the recorder images and other data from STEREO's instruments, which can then be sent back to Earth.

New Horizons

New Horizons



Operator	NASA
Major contractors	APL, SwRI
Mission type	Flyby
Flyby of	APL, Jupiter, Pluto, Charon, Hydra, Nix
Flyby date	2015-07-14 (projected)
Launch date	2006-01-19 19:00:00 UTC (4 years, 11 months, and 29 days elapsed)
Launch vehicle	Atlas V 551
Launch site	Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	In transit (Pluto) (4 years, 11 months, and 29 days elapsed) APL flyby (completed 2006-06-13) Jupiter flyby (completed 2007-02-28)
COSPAR ID	2006-001A

Homepage pluto.jhuapl.edu
Mass 478 kg (1,050 lb)
Power 228 W (RTG)
Orbital elements
Inclination negligible As of 2010



New Horizons mission logo

Background

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

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

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

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

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

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

Launch



New Horizons at lift-off

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



Space Launch Complex 41 during *New Horizons* launch

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

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

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



New Horizons probe launched from Cape Canaveral on January 19, 2006

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

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

Trajectory corrections and instrument testing

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

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

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

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

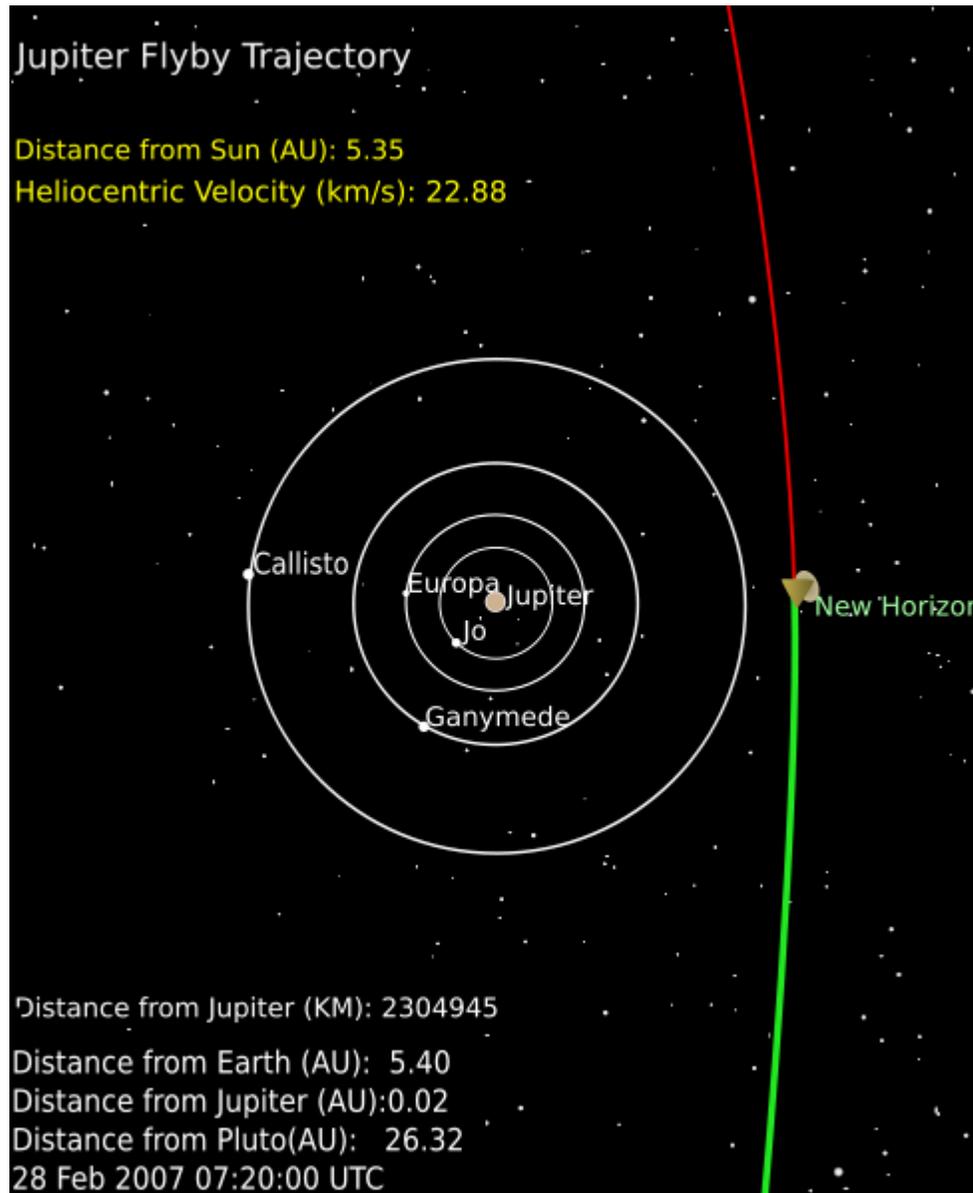
Passing Mars orbit and asteroid flyby

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

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

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

Jupiter gravity assist



New Horizons at periapsis with Jupiter on February 28, 2007

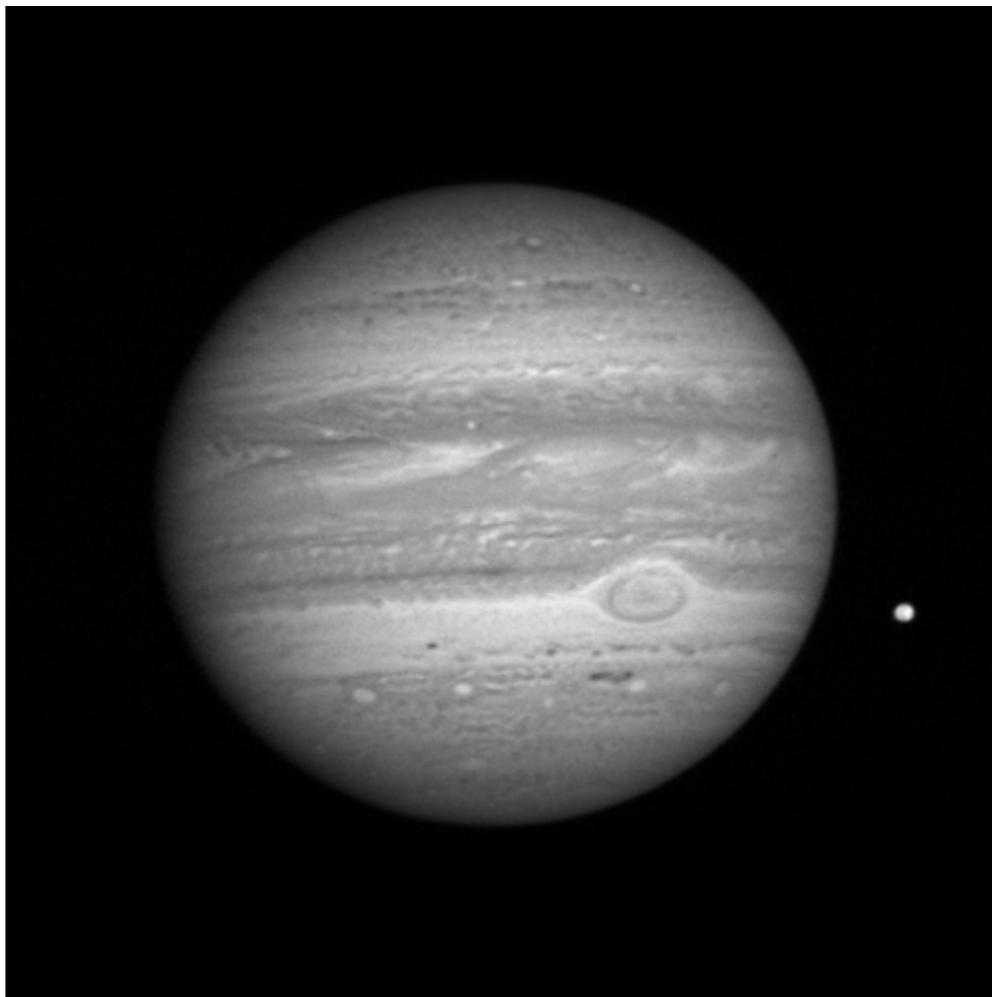
New Horizons' Long Range Reconnaissance Imager (LORRI) took its first photographs of Jupiter on September 4, 2006. The spacecraft began further study of the Jovian system in December 2006.

New Horizons received a Jupiter gravity assist with a closest approach at 5:43:40 UTC (12:43:40am EST) on February 28, 2007. It passed through the Jupiter system at 21 km/s (47,000 mph) relative to Jupiter (23 km/s (51,000 mph) relative to the Sun). The flyby increased *New Horizons'* speed away from the Sun by nearly 4 km/s (8,900 mph), putting

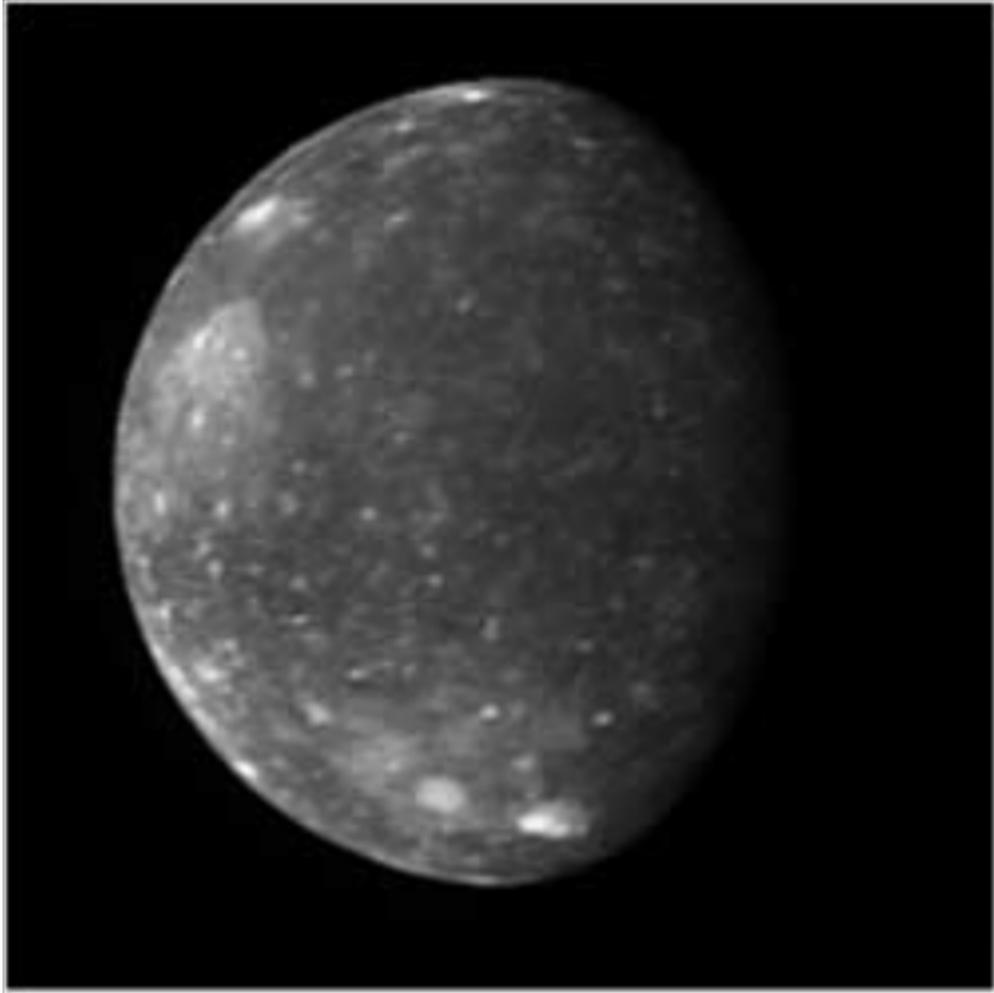
the spacecraft on a faster trajectory to Pluto, about 2.5 degrees out of the plane of the Earth's orbit (the "ecliptic"). As of November, 2009, the gravitational attraction of the Sun has slowed down the spacecraft to about 16.656 km/s (37,260 mph). *New Horizons* was the first probe launched directly toward Jupiter since the *Ulysses* probe in 1990.

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

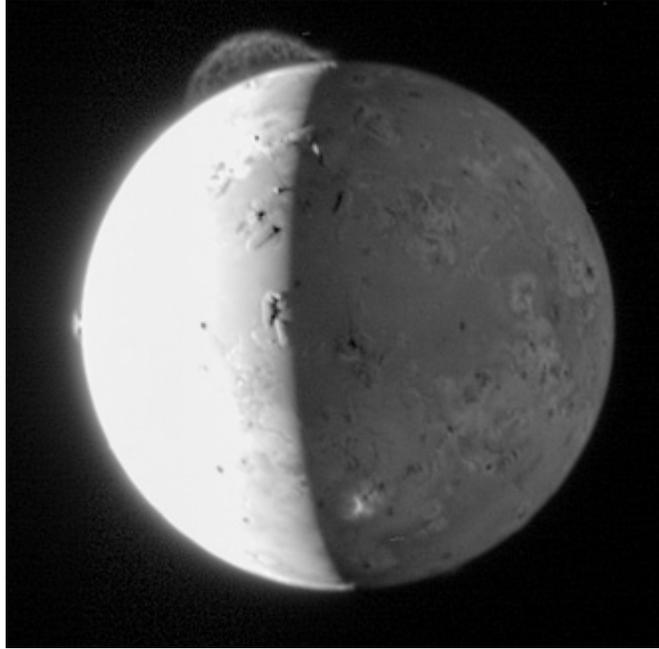
Jovian system imaged by *New Horizons*



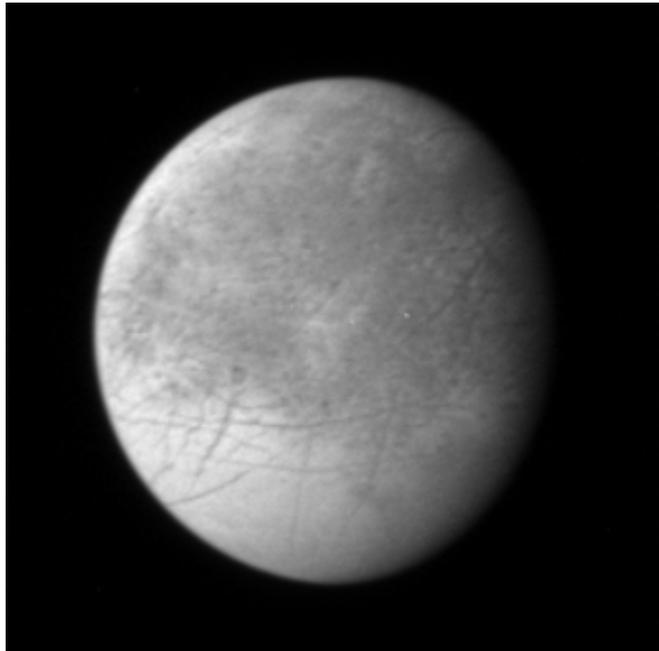
Jupiter and its moon *Io* imaged by *New Horizons* during flyby



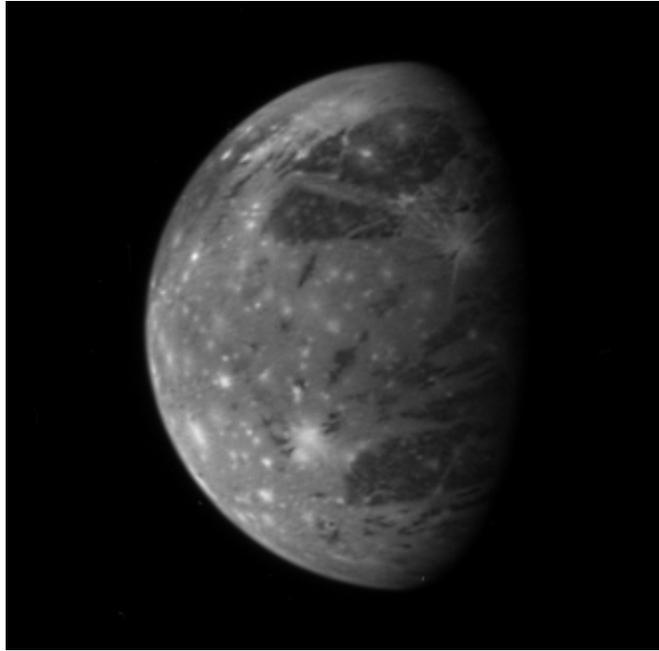
Callisto imaged by *New Horizons* during flyby



Io imaged by *New Horizons* during flyby

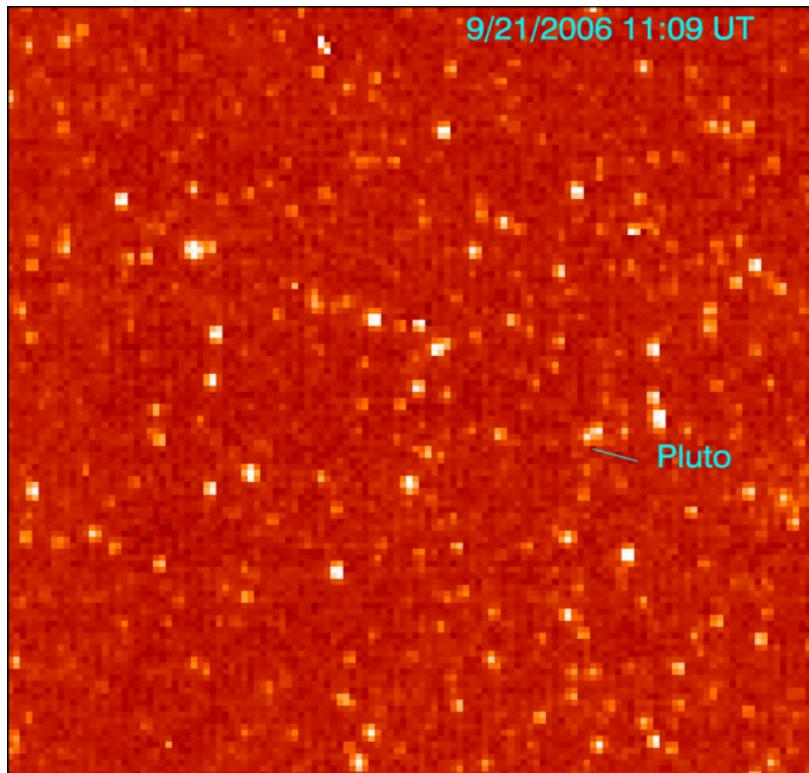


Europa imaged by *New Horizons* during flyby



Ganymede imaged by *New Horizons* during flyby

Pluto approach



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

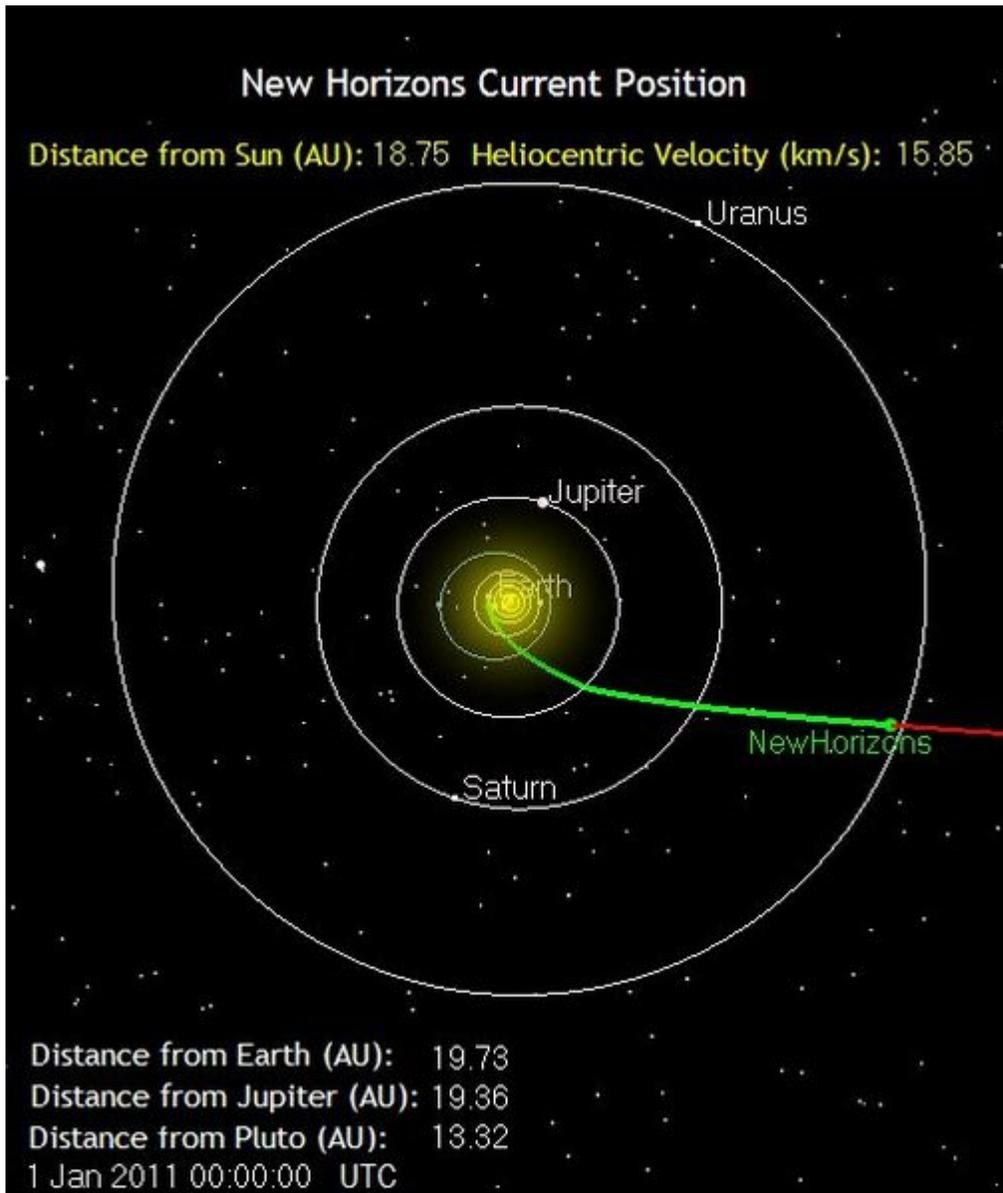
The first images of Pluto from *New Horizons* were created between September 21–24, 2006, during a test of the LORRI. They were released on November 28. The images, taken from a distance of approximately 4.2 billion kilometers (2.6 billion miles), confirmed the spacecraft's ability to track distant targets,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

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

Kuiper belt mission

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

Key mission dates



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

- June 8, 2001 — New Horizons picked by NASA over a competing design, POSSE (Pluto and Outer Solar System Explorer).
- June 13, 2005 — Spacecraft departed APL for final testing at Goddard Space Flight Center (GSFC).
- September 24, 2005 — Spacecraft shipped to Cape Canaveral, through Andrews Air Force Base, aboard a C-17 Globemaster III cargo aircraft.
- December 17, 2005 — Transported from Hazardous Servicing Facility to Vertical Integration Facility at Space Launch Complex 41.

- January 11, 2006 — Primary launch window opened. Launch delayed for further testing.
- January 16, 2006 — Atlas V launcher, serial number AV-010, rolled out onto pad.
- January 17, 2006 — First day launch attempts scrubbed because of unacceptable weather conditions (high winds).
- January 18, 2006 — Second launch attempt scrubbed because of morning power outage at the Applied Physics Laboratory.
- January 19, 2006 — **Successful launch** at 14:00 EST (19:00 UTC) after brief delay due to cloud cover.
- April 7, 2006 — The probe passed Mars' orbit.
- Early May, 2006 — The probe entered the asteroid belt.
- June 13, 2006 — The probe passed closest to the asteroid 132524 APL in the Belt at about 101,867 km at 04:05 UTC. Pictures were taken.
- Late October, 2006 — The probe left the asteroid belt.
- November 28, 2006 — First faint image of Pluto taken from a distance released.
- January 8, 2007 — Start of Jupiter encounter.
- January 10, 2007 — Long distance observations of outer moon Callirrhoe as a navigation exercise.
- February 28, 2007 — Jupiter flyby. Closest approach occurred at 05:43:40 UTC at 2.305 million km, 21.219 km/s.
- March 5, 2007 — End of Jupiter encounter phase.
- June 8, 2008 — The probe passed Saturn's orbit.
- December 29, 2009 — The probe became closer to Pluto than to Earth
- March 8, 2010 - Distant flyby of 83982 Crantor
- October 17, 2010 — As of 4.25 UTC, half the mission time between launch and closest approach had elapsed, with 1731 days, 8 hours and 25 minutes remaining to closest approach and having elapsed since launch.

Planned

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

Spacecraft subsystems

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

Structural

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



New Horizons in its assembly hall

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

Propulsion and attitude control

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

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

Power

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

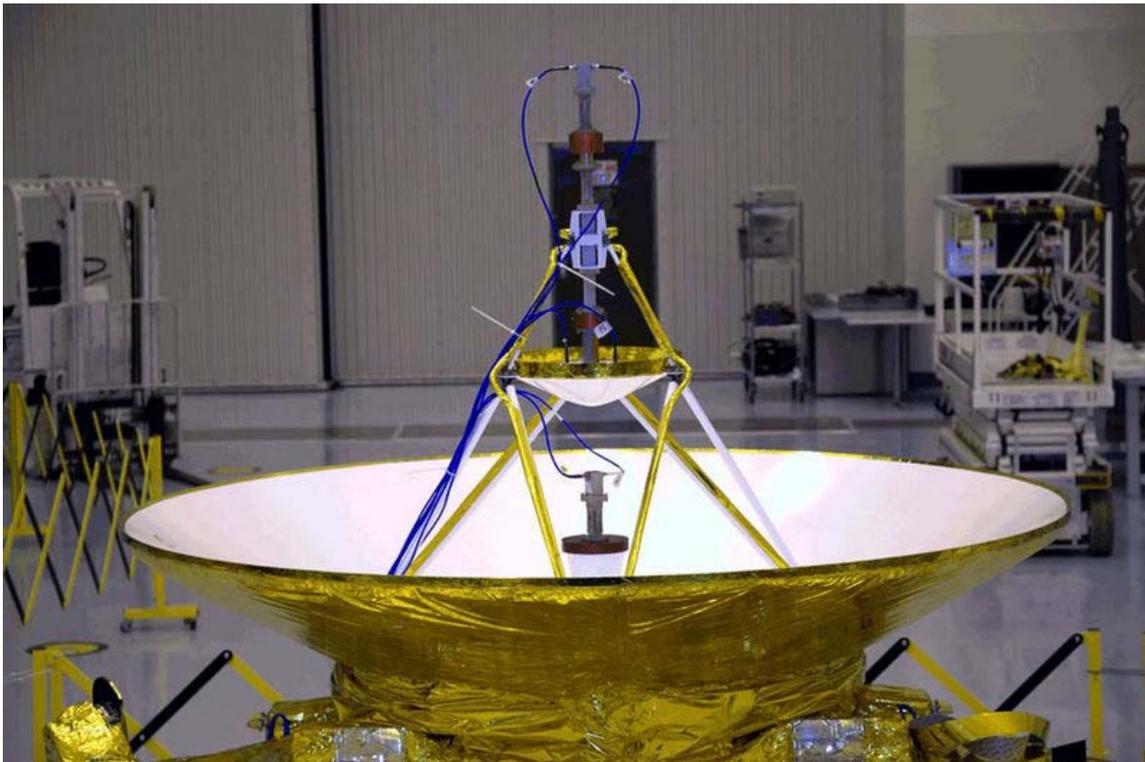
The use of a plutonium RTG battery resulted in minor demonstrations some days before launch by about 30 anti-nuclear protesters. The amount of radioactive plutonium in the RTG is 10.9 kg, about one-third the amount on-board the Cassini-Huygens probe when it launched in 1997. That launch was protested by over 300 people. The United States Department of Energy estimated the chances of a launch accident that would release radiation into the atmosphere at 1 in 350 and monitored the launch as it always does when RTGs are involved. It was believed that a worst-case scenario of total dispersal of on-board plutonium would spread the equivalent radiation of 80% the average annual dosage in North America from background radiation over an area with a radius of 65 miles (105 km), with cleanup costing anywhere from \$241 million – \$1.2 billion USD per square mile. at the Materials and Fuels Complex (formerly Argonne West), a part of the Idaho National Laboratory in Bingham County, near the town of Arco and the city of Idaho Falls. The plutonium was produced at Los Alamos National Laboratory in New Mexico. Less than the original design goal was produced, due to delays at the United

States Department of Energy, including security activities, which held up production. The mission parameters and observation sequence had to be modified for the reduced wattage; still, not all instruments can operate simultaneously. The Department of Energy transferred the space battery program from Ohio to Argonne in 2002 because of security concerns. There are no onboard batteries. RTG output is relatively predictable; load transients are handled by a capacitor bank and fast circuit breakers.

Thermal

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

Telecommunications



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

Communication with the spacecraft is via X band.

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

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

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

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

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

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

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

Data handling

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

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

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

Chapter- 7

Space and Solar System Exploration in 2007

Dawn (spacecraft)

Dawn



Artist's concept of *Dawn* with Vesta (left) & Ceres (right)
(the proximity of Vesta to Ceres is not to scale.)

Operator	NASA
Major contractors	Orbital Sciences, JPL, UCLA
Mission type	Flyby / Orbiter
Flyby of	Mars
Satellite of	Vesta, Ceres
Orbital insertion date	Vesta: July 2011 (projected) Ceres: February 2015 (projected)

Launch date	2007-09-27 11:34:00 UTC (3 years, 141 days ago)
Launch vehicle	Delta II 7925H Space Launch Complex 17B
Launch site	Cape Canaveral Air Force Station In Transit
Mission duration	Mars flyby (completed 2009-02-04)
COSPAR ID	2007-043A
Mass	1,250 kg (2,800 lb)
Power	1000 W (Solar array)

Orbital elements

Eccentricity	~ circular
Inclination	Polar

Dawn is a robotic spacecraft sent by NASA on a space exploration mission to the two most massive members of the asteroid belt: Vesta and the dwarf planet Ceres. Launched on September 27, 2007, *Dawn* is scheduled to explore Vesta between 2011 and 2012, and Ceres in 2015. It will be the first spacecraft to visit either body.

Dawn is innovative in that it will be the first spacecraft to enter into orbit around a celestial body, study it, and then re-embark under powered flight to proceed to a second target. All previous multi-target study missions—such as the Voyager program—have involved rapid planetary flybys.

The Dawn mission to Vesta and Ceres is managed by NASA's Jet Propulsion Laboratory, a division of the California Institute of Technology in Pasadena, for NASA's Science Mission Directorate, Washington.

Launch

Dawn was scheduled to launch from pad 17-B at the Cape Canaveral Air Force Station on a Delta 7925-H rocket. On April 10, 2007, *Dawn* arrived at the Astrotech Space Operations subsidiary of SPACEHAB, Inc. in Titusville, Florida, where it was prepared for launch. Launch was originally scheduled for June 20, but was delayed until June 30 due to delays with part deliveries. A broken crane at the launch pad, used to raise the

solid rocket boosters, delayed the launch for a week, until July 7, but on June 15 the second stage was successfully hoisted into position. A mishap at the Astrotech Space Operations facility, involving slight damage to one of the solar arrays, did not have an effect on the launch date; however, bad weather caused the launch to slip to July 8. Range tracking problems then delayed the launch to July 9, and then July 15, before the launch was delayed further to avoid knock-on delays with the Phoenix mission to Mars, which was successfully launched on August 4.



A Delta II launching *Dawn* from CCAFS SLC-17

Launch of *Dawn* was then rescheduled for September 26, 2007, then September 27, due to bad weather delaying fueling of the second stage, the same problem which had earlier delayed the July 7 launch attempt. The launch window extended from 07:20 – 07:49 EDT

(11:20 – 11:49 GMT). During the final built-in hold at T-4 minutes, a ship entered the exclusion area offshore, the sea strip where the rocket boosters were likely to fall after separation. The ship was commanded to leave the area, then the launch had to wait for the end of a collision avoidance window with the International Space Station. The spacecraft launched at 07:34 EDT from pad 17-B on a Delta II launch vehicle.

The launch rocket propelled *Dawn* to 11.46 kilometers per second (25,600 miles per hour) relative to earth. Thereafter *Dawn's* ion thrusters took over.

Status

After initial checkout, during which the ion thrusters accumulated more than 11 days of thrust, *Dawn* began long-term cruise propulsion on December 17, 2007. On October 31, 2008, *Dawn* completed its first thrusting phase to send it on to Mars for a gravity assist flyby in February 2009. During this first interplanetary cruise phase *Dawn* spent 270 days, or 85% of this phase using its thrusters. It expended less than 72 kilograms (158 pounds) of xenon propellant for a total change in velocity of 1.81 kilometers per second (4050 miles per hour). On November 20, 2008, *Dawn* performed its first trajectory correction maneuver (TCM1), firing its number 1 thruster for 2 hours, 11 minutes. Following *Dawn's* solar conjunction, an originally scheduled course correction maneuver in January 2009 was determined not necessary.

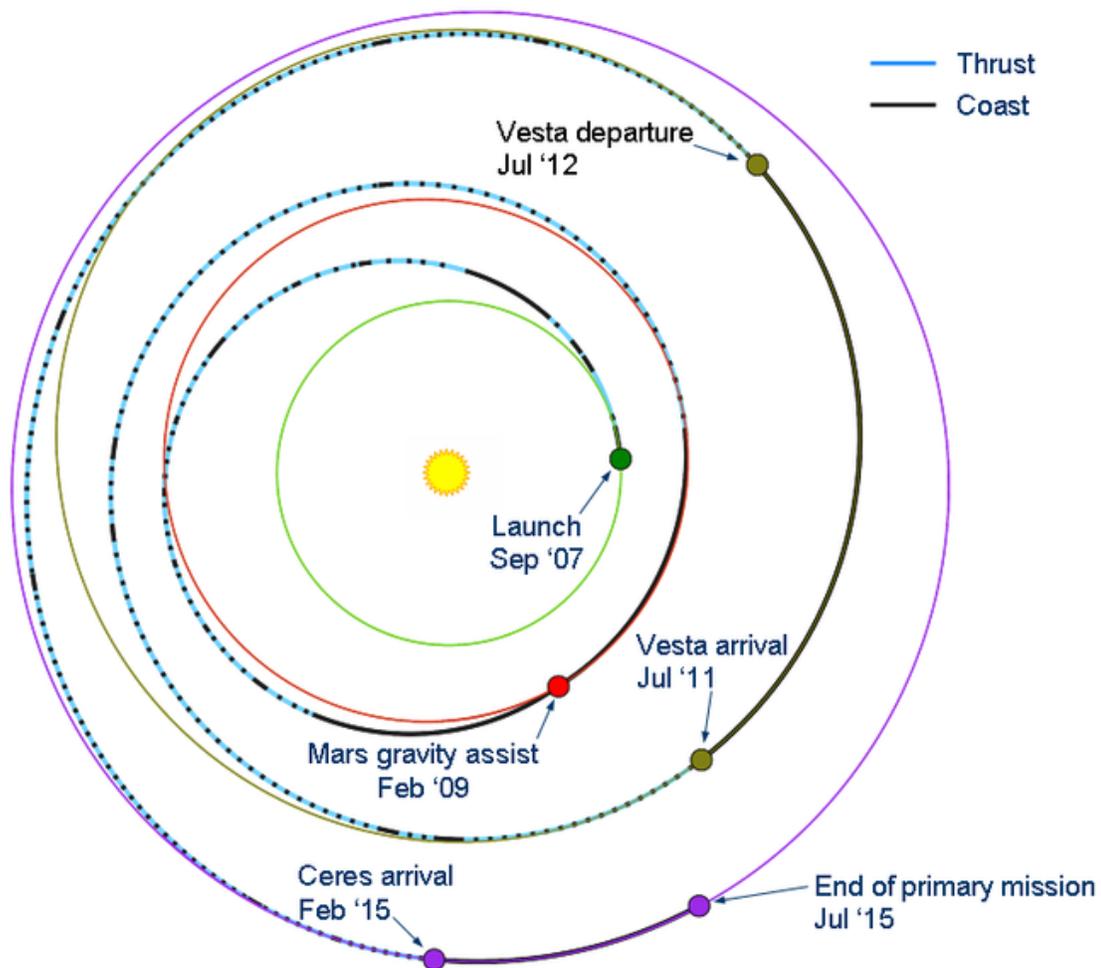
Dawn made its closest approach (549 km) to Mars on February 17, 2009 during a successful gravity assist. On this day the spacecraft placed itself in safe mode resulting in some data acquisition loss. The spacecraft was reported to be back in full operation two days later with no impact to the subsequent mission. The root cause of the event was reported to be a software programming error.

Mission

The mission's goal is to characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest protoplanets remaining intact since their formation. Ceres and Vesta have many contrasting characteristics that are thought to have resulted from them forming in two different regions of the early solar system; Peter Thomas of Cornell University has proposed that Ceres has a differentiated interior; its oblateness appears too small for an undifferentiated body, which indicates that it consists of a rocky core overlain with an icy mantle. There is a large collection of potential samples from Vesta accessible to scientists, in the form of over 200 HED meteorites, giving insight into Vestian geologic history and structure. Vesta is thought to consist of a metallic iron–nickel core, an overlying rocky olivine mantle, with a surface crust.

Using two redundant framing cameras, a visual and infrared spectrometer, and a Gamma Ray and Neutron Spectrometer, *Dawn* will take pictures and measure the chemical composition of Ceres and Vesta.

To cruise from Earth to its targets it will travel in a long outward spiral. The estimated chronology is as follows:



Planned flight trajectory

- September 27, 2007: launch
- February 17, 2009: Mars gravity assist
- July 2011: Vesta arrival
- July 2012: Vesta departure
- February 2015: Ceres arrival
- July 2015: End of primary operations

NASA posts the current location of *Dawn* on the web.

An extended mission following the completion of the Ceres study is also possible, although unlikely, as greater return is expected by spending the available time at Vesta and Ceres. Although 2 Pallas would have been a feasible extended target for the originally scheduled launch date, launch delays have meant that this may no longer be the

case. Fuel was also not specifically allocated to break orbit from Ceres, and will depend upon the details of the flight reaching Ceres.

Mission team

The *Dawn* mission team is led by UCLA space scientist and *Dawn* Principal Investigator Christopher T. Russell. NASA's Jet Propulsion Laboratory provided overall planning and management of the mission, the flight system and scientific payload development, and provided the Ion Propulsion System. Orbital Sciences Corporation provided the spacecraft, which constituted the company's first interplanetary mission. The Max Planck Institute for Solar System Research and the German Aerospace Center (DLR) provided the framing cameras, the Italian Space Agency provided the mapping spectrometer, and the DOE Los Alamos National Laboratory provided the gamma ray and neutron spectrometer.

Motivation



Dawn waits for encapsulation at its launch pad on July 1, 2007

Dawn is intended to study two large bodies in the asteroid belt in order to answer questions about the formation of the solar system.

Ceres and Vesta were chosen as two contrasting protoplanets, the first one apparently "wet" (that is, icy) and the other "dry" (or rocky), whose accretion was terminated by the formation of Jupiter. They provide a bridge in our understanding between the formation of rocky planets and the icy bodies of our solar system, and under what conditions a rocky planet can hold water.

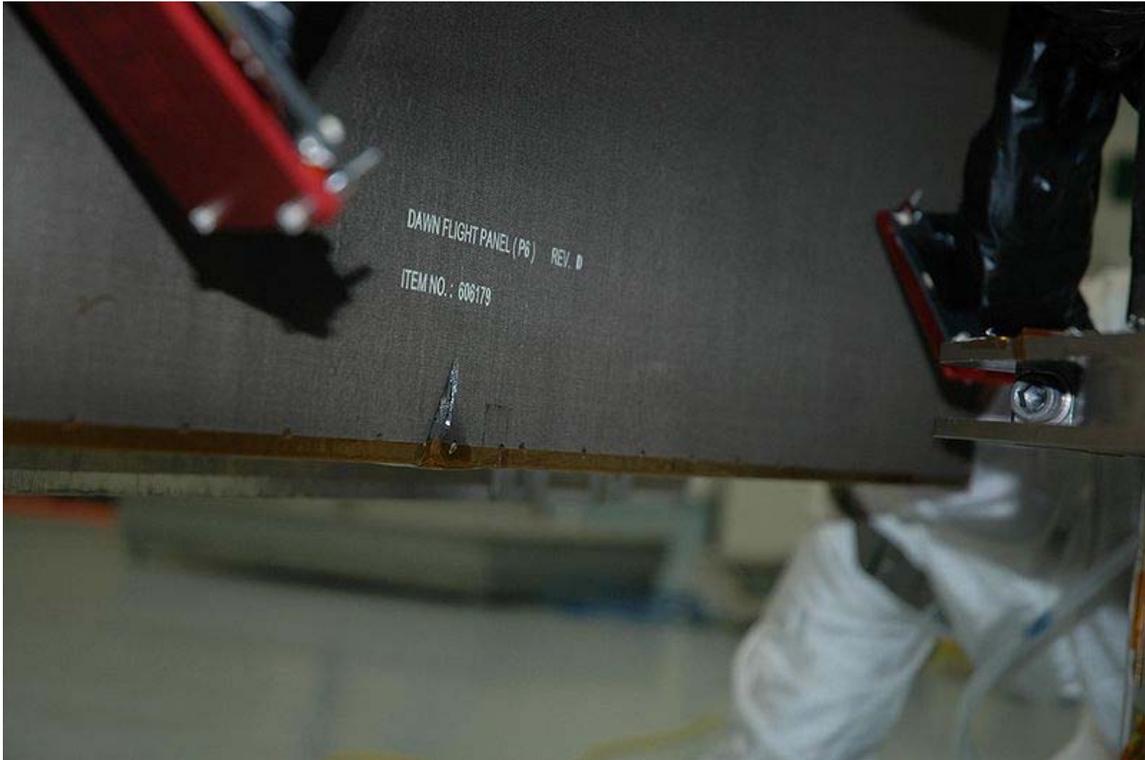
The IAU adopted a new definition of planet on August 24, 2006, and thus, if the IAU's definition stands and the spacecraft experiences no delays, *Dawn* will become the first mission to study a dwarf planet, arriving at Ceres five months prior to the arrival of *New Horizons* at Pluto.

Ceres is a dwarf planet whose mass comprises about one-third of the total mass of the bodies in the asteroid belt and whose spectral characteristics suggest a composition similar to that of a water-rich carbonaceous chondrite. Smaller Vesta, a water-poor achondritic asteroid, has experienced significant heating and differentiation. It shows signs of a metallic core, a Mars-like density and lunar-like basaltic flows.

Both bodies formed very early in the history of the solar system, thereby retaining a record of events and processes from the time of the formation of the terrestrial planets. Radionuclide dating of pieces of meteorites thought to come from Vesta suggests that Vesta differentiated quickly, in only three million years. Thermal evolution studies suggest that Ceres must have formed a little later, more than three million years after the formation of CAIs (the oldest known objects of Solar System origin).

Moreover, Vesta is the source of many smaller objects in the solar system. Most (but not all) V-type near-Earth asteroids, and some outer main-belt asteroids have spectra similar to Vesta and are known as *vestoids*. Five percent of the found meteoritic samples on Earth, the Howardite Eucrite Diogenite ("HED") meteorites, are thought to be the result of a collision or collisions with Vesta.

Mission cancellations and reinstatements



The slightly damaged solar array (NASA)

The status of the *Dawn* mission has changed several times. In December 2003, the project was first cancelled, and then reinstated in February 2004. In October 2005, work on *Dawn* was placed in "stand down" mode. In January 2006, *Dawn's* "stand down" was discussed in the press as "indefinitely postponed", even though NASA had announced no new decisions regarding the mission's status. On March 2, 2006, *Dawn* was publicly, but not formally canceled by NASA headquarters.

The spacecraft's manufacturer Orbital Sciences Corporation appealed the decision and offered to build the spacecraft at cost, forgoing any profit in order to gain experience in a new market field. NASA then put the cancellation under review, and on March 27, 2006, it was announced that the mission would not be canceled after all. In the last week of September 2006, the *Dawn* mission instrument payload integration reached a full functional status.

Propulsion system

The *Dawn* spacecraft is propelled by three DS1 heritage xenon ion thrusters (firing only one at a time). They have a specific impulse of 3,100 s and produce a thrust of 90 mN. The whole spacecraft, including the ion propulsion thrusters, is powered by a 10 kW triple-junction photovoltaic solar array. To get to Vesta, *Dawn* is allocated 275 kg

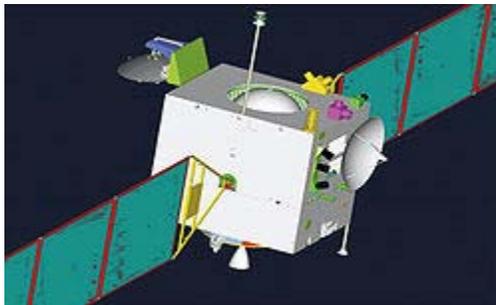
(606 lb) Xe, with another 110 kg (243 lb) to reach Ceres, out of a total capacity of 425 kg (937 pounds) of on-board propellant. All in all, it will perform a velocity change of over 10 km/s, far more than any other spacecraft has done after being propelled by its launch rocket. *Dawn* is NASA's first purely exploratory mission to use ion propulsion engines.

The *Dawn* microchip

Onboard *Dawn* is a small computer microchip bearing the names of more than 360,000 space enthusiasts. The names were submitted online as part of a public outreach effort between September 2005 and November 4, 2006. The microchip (about the size of a nickel) was installed above the forward ion thruster, underneath the spacecraft's High Gain Antenna, on May 17, 2007. More than one microchip was made, with a back-up copy on display at the *2007 Open House* at the Jet Propulsion Laboratory in Pasadena, California.

Chang'e 1

Chang'e 1



Operator	China National Space Administration (CNSA)
Mission type	Orbiter / impactor
Satellite of	The moon
Launch date	2007-10-24, 10:05:04.602 UTC
Carrier rocket	Long March 3A
Launch site	Xichang Satellite Launch Center, Launch Pad 3 Xichang, The People's Republic of China

Mission duration 2009-03-01, 08:13:10 UTC
1 year, 4 months, 4 days, 22 hours and 7 minutes

COSPAR ID 2007-051A

Homepage CLEP

Mass 2,350 kg

Orbital elements

Inclination ~64°

Apoapsis ~200 km

Periapsis ~200 km

Orbital period ~127 minutes

Chang'e 1 (pronounced *chang-uh*; simplified Chinese: 嫦娥一号; traditional Chinese: 嫦娥一號; pinyin: *Cháng'é yī hào*) was an unmanned Chinese lunar-orbiting spacecraft, part of the first phase of the Chinese Lunar Exploration Program. The spacecraft was named after the Chinese moon goddess, Chang'e.

Chang'e 1 was launched on 24 October 2007 at 10:05:04 UTC from Xichang Satellite Launch Center. It left lunar transfer orbit on 31 October and entered lunar orbit on 5 November. The first picture of the Moon was relayed on 26 November 2007. On 12 November 2008, a map of the entire lunar surface was released, produced from data collected by Chang'e 1 between November 2007 and July 2008.

The mission was scheduled to continue for a year, but was later extended and the spacecraft operated until 1 March 2009, when it was taken out of orbit. It impacted the surface of the Moon at 08:13 UTC. Data gathered by Chang'e 1 was able to create the most accurate and highest resolution 3-D map ever created of the lunar surface. Its sister orbital probe Chang'e 2 was launched on the first of October 2010.

Objectives

The Chang'e 1 mission had four major goals:

1. Obtaining three-dimensional images of the landforms and geological structures of the lunar surface, so as to provide a reference for planned future soft landings. The orbit of Chang'e 1 around the Moon was designed to provide complete coverage, including areas near the north and south poles not covered by previous missions.

2. Analysing and mapping the abundance and distribution of various chemical elements on the lunar surface as part of an evaluation of potentially useful resources on the Moon. China hopes to extend the number of elements studied to 14 (potassium (K), thorium (Th), uranium (U), oxygen (O), silicon (Si), magnesium (Mg), aluminum (Al), calcium (Ca), tellurium (Te), titanium (Ti), sodium (Na), manganese (Mn), chromium (Cr), and lanthanum (La)), compared with the 10 elements (K, U, Th, Fe (iron), Ti, O, Si, Al, Mg, and Ca) previously probed by NASA's Lunar Prospector.
3. Probing the features of the lunar soil and assessing its depth, as well as the amount of helium-3 (^3He) present.
4. Probing the space environment between 40,000 km and 400,000 km from the Earth, recording data on the solar wind and studying the impact of solar activity on the Earth and the Moon.

In addition, the lunar probe engineering system, composed of five major systems – the satellite system, the launch vehicle system, the launch site system, the monitoring and control system and the ground application system – accomplished five goals:

- Researching, developing and launching China's first lunar probe
- Mastering the basic technology of placing satellites in lunar orbit
- Conducting China's first scientific exploration of the Moon
- Initially forming a lunar probe space engineering system
- Accumulating experience for the later phases of China's lunar exploration program

Mission



The launch of Chang'e 1 at Xichang Satellite Launch Center

According to the schedule, detailed design of the first program milestone was completed by September 2004. Research and development of a prototype probe and relevant testing of the probe were finished before the end of 2005. Design, manufacture, general assembly, test and ground experiments of the lunar orbiter were finished before December 2006.

Originally scheduled for April 2007, the launch was postponed until October as this was "a better time for sending a satellite into the moon's orbit". Chang'e 1 was launched by a Long March 3A rocket at 10:05 GMT on October 24, 2007 from Xichang Satellite Launch Center in Sichuan Province.

After liftoff, Chang'e 1 made three orbits around the Earth, a burn at perigee extending the orbit's apogee further each time, until a final translunar injection burn placed it on course for the Moon on October 31, 2007. Another burn placed it in a polar orbit around the Moon, with burns at the perilune of the first three orbits decreasing the apolune until it entered a final circular orbit. Lunar orbit insertion was achieved on the November 5, 2007. To mark this occasion, the probe transmitted 30 classical Chinese songs and

musical pieces, including "My Motherland", "The Song of the Yangtze River", and "High Mountains and Flowing Water".

The probe was remotely controlled from stations at Qingdao and Kashgar. As well as Chinese facilities, the ESA Maspalomas Tracking Station was used to transmit signals to and from the probe.

The first pictures of the Moon were relayed on November 26, 2007. The probe was designed to orbit the Moon for one year, but operations were later extended, and it remained in lunar orbit until March 1, 2009.

End of mission

On 1 March 2009, at 08:13:10 UTC, Chang'e 1 crashed onto the surface of the Moon, ending its mission. According to the State Administration of Science, Technology and Industry for National Defense (China), this was a planned and controlled impact. Impact point was 1°30'S 52°22'E / 1.50°S 52.36°E. During its orbital mission the probe transmitted 1,400 gigabits or 175 gigabytes (GB) of data.

Design and instrumentation

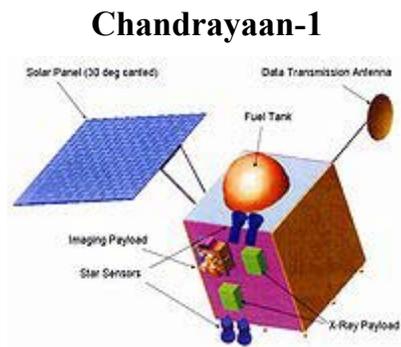
The Chang'e 1 spacecraft had a mass of 2,350 kg, with a 130 kg payload, carrying 24 instruments including a Charge-coupled device (CCD) stereo camera, microprobe instruments, and a high-energy solar particle detector.

- Stereo camera with an optical resolution of 120 m and spectrometer imager operating at wavelengths of 0.48 μm to 0.96 μm .
- Laser altimeter with 1064 nm, 150 mJ laser, a range resolution of 1 m and a spot size of 300 m.
- Imaging spectrometer
- Gamma and X-ray spectrometer working in an energy range of 0.5 to 50 keV for X-rays and 300 keV to 9 MeV for gamma rays.
- Microwave radiometer detecting 3, 7.8, 19.35 and 37 GHz with a maximal penetration depth of 30, 20, 10, 1 m and a thermal resolution of 0.5 K.
- High energy particle detector and two solar wind detectors capable of the detection of electrons and heavy ions up to 730 MeV.

Chapter- 8

Space and Solar System Exploration in 2008

Chandrayaan-1



Configuration of Chandrayaan-1 that lift off on the PSLV-C11

Operator	Indian Space Research Organisation
Mission type	Orbiter
Satellite of	Moon
Orbital insertion date	12 November 2008
Orbits	3400 orbits around the Moon.
Launch date	22 October 2008 00:52 UTC
Launch vehicle	PSLV-C11
Launch site	SDSC, Sriharikota

Mission	Intended: 2 years
duration	Achieved: 312 days
COSPAR ID	2008-052A
Homepage	Chandrayaan-1
Mass	1,380 kg (3,042 lb)

Orbital elements

Eccentricity	near circular
Inclination	polar
Apoapsis	initial 7,500 km (4,660 mi), final 100 km (62 mi), final (wef 19 May 2009) 200 km (124 mi)
Periapsis	initial 500 km (311 mi), final 100 km (62 mi), final (wef 19 May 2009) 200 km (124 mi)

Chandrayaan-1 (Sanskrit: चंद्रयान-१, lit: moon vehicle) was India's first unmanned lunar probe. It was launched by the Indian Space Research Organisation in October 2008, and operated until August 2009. The mission included a lunar orbiter and an impactor. India launched the spacecraft with a modified version of the PSLV, PSLV C11 on 22 October 2008 from Satish Dhawan Space Centre, Sriharikota, Nellore District, Andhra Pradesh, about 80 km north of Chennai, at 06:22 IST (00:52 UTC). Former prime minister Atal Bihari Vajpayee announced the project on course in his Independence Day speech on 15 August 2003. The mission was a major boost to India's space program, as India researched and developed its own technology in order to explore the Moon. The vehicle was successfully inserted into lunar orbit on 8 November 2008.

On 14 November 2008, the Moon Impact Probe separated from the Chandrayaan orbiter at 20:06 and struck the south pole in a controlled manner, making India the fourth country to place its flag on the Moon. The probe impacted near Shackleton Crater at 20:31 ejecting underground soil that could be analysed for the presence of lunar water ice.

The estimated cost for the project was ₹386 crore (US\$80 million).

The remote sensing lunar satellite had a mass of 1,380 kilograms (3,042 lb) at launch and 675 kilograms (1,488 lb) in lunar orbit. It carried high resolution remote sensing equipment for visible, near infrared, and soft and hard X-ray frequencies. Over a two-year period, it was intended to survey the lunar surface to produce a complete map of its

chemical characteristics and three-dimensional topography. The polar regions are of special interest as they might contain ice. The lunar mission carries five ISRO payloads and six payloads from other space agencies including NASA, ESA, and the Bulgarian Aerospace Agency, which were carried free of cost.

After suffering from several technical issues including failure of the star sensors and poor thermal shielding, Chandrayaan stopped sending radio signals at 1:30 AM IST on 29 August 2009 shortly after which, the ISRO officially declared the mission over. Chandrayaan operated for 312 days as opposed to the intended two years but the mission achieved 95 percent of its planned objectives. Among its many achievements was the discovery of the widespread presence of water molecules in lunar soil.

Objectives

The stated scientific objectives of the mission were:

- to design, develop, launch and orbit a spacecraft around the Moon using an Indian-made launch vehicle
- to conduct scientific experiments using instruments on the spacecraft which would yield data:
 - for the preparation of a three-dimensional atlas (with high spatial and altitude resolution of 5–10 m) of both the near and far side of the Moon
 - for chemical and mineralogical mapping of the entire lunar surface at high spatial resolution, mapping particularly the chemical elements magnesium, aluminium, silicon, calcium, iron, titanium, radon, uranium, and thorium
 - to increase the scientific knowledge
 - to test the impact of a sub-satellite (Moon Impact Probe — MIP) on the surface on the Moon as a fore-runner to future soft-landing missions

Specifications

Mass

1,380 kg at launch, 675 kg at lunar orbit, and 523 kg after releasing the impactor.

Dimensions

Cuboid in shape of approximately 1.5 m

Communications

X band, 0.7 m diameter dual gimballed parabolic antenna for payload data transmission. The Telemetry, Tracking & Command (TTC) communication operates in S band frequency.

Power

The spacecraft is mainly powered by its solar array, which includes one solar panel covering a total area of 2.15 x 1.8 m generating 750 W of peak power, which is stored in a 36 A·h lithium-ion battery for use during eclipses.

Propulsion

The spacecraft uses a bipropellant integrated propulsion system to reach lunar orbit as well as orbit and altitude maintenance while orbiting the Moon. The power plant consists of one 440 N engine and eight 22 N thrusters. Fuel and oxidizer are stored in two tanks of 390 litres each.

Navigation and control

The craft is 3-axis stabilized with two star sensors, gyros and four reaction wheels. The craft carries dual redundant bus management units for attitude control, sensor processing, antenna orientation, etc.

Specific areas of study

- High-resolution mineralogical and chemical imaging of the permanently shadowed north- and south-polar regions
- Searching for surface or sub-surface lunar water-ice, especially at the lunar poles
- Identification of chemicals in lunar highland rocks
- Chemical stratigraphy of the lunar crust by remote sensing of the central uplands of large lunar craters, and of the South Pole Aitken Region (SPAR), an expected site of interior material
- Mapping the height variation of features of the lunar surface
- Observation of X-ray spectrum greater than 10 keV and stereographic coverage of most of the Moon's surface with 5 m resolution
- Providing new insights in understanding the Moon's origin and evolution

Payloads

The scientific payload had a total mass of 90 kg and contained five Indian instruments and six foreign instruments.

Indian Payloads

- **TMC** or the **Terrain Mapping Camera** is a CCD camera with 5 m resolution and a 40 km swath in the panchromatic band and was used to produce a high-resolution map of the Moon. The aim of this instrument was to completely map the topography of the Moon. The camera works in the visible region of the electromagnetic spectrum and captures black and white stereo images. When used in conjunction with data from Lunar Laser Ranging Instrument (LLRI), it can help in better understanding of the lunar gravitational field as well. TMC was built by the ISRO's Space Applications Centre (SAC) at Ahmedabad. The TMC was successfully tested on 29 October 2008 through a set of commands issued from ISTRAC.
- **HySI** or **Hyper Spectral Imager** performed mineralogical mapping in the 400-900 nm band with a spectral resolution of 15 nm and a spatial resolution of 80 m.

- **LLRI or Lunar Laser Ranging Instrument** determines the height of the surface topography by sending pulses of infrared laser light towards the lunar surface and detecting the reflected portion of that light. It operated continuously and collected 10 measurements per second on both the day and night sides of the Moon. It was successfully tested on 16 November 2008.
- **HEX is a High Energy α /gamma x-ray spectrometer** for 30 – 200 keV measurements with ground resolution of 40 km, the HEX measured U, Th, ^{210}Pb , ^{222}Rn degassing, and other radioactive elements.
- **MIP or the Moon Impact Probe** developed by the ISRO, is an impact probe which consisted of a C-band Radar altimeter for measurement of altitude of the probe, a video imaging system for acquiring images of the lunar surface and a mass spectrometer for measuring the constituents of the lunar atmosphere. It was ejected at 20:00 hours IST on 14 November 2008. The Moon Impact Probe successfully crash landed at the lunar south pole at 20:31 hours IST on 14 November 2008. It carried with it a picture of the Indian flag. India is now the fourth nation to place a flag on the Moon after the Soviet Union, United States and Japan.

Payload from other countries

- **CIXS or X-ray fluorescence spectrometer** covering 1- 10 keV, mapped the abundance of Mg, Al, Si, Ca, Ti, and Fe at the surface with a ground resolution of 25 km, and monitored solar flux. This payload results from collaboration between Rutherford Appleton laboratory, U.K, ESA and ISRO. It was activated on 23 November 2008.
- **SARA, The Sub-keV Atom Reflecting Analyser** from the ESA mapped mineral composition using low energy neutral atoms emitted from the surface.
- **M³, the Moon Mineralogy Mapper** from Brown University and JPL (funded by NASA) is an imaging spectrometer designed to map the surface mineral composition. It was activated on 17 December 2008.
- **SIR-2**, A near infrared spectrometer from ESA, built at the Max Planck Institute for Solar System Research, Polish Academy of Science and University of Bergen, also mapped the mineral composition using an infrared grating spectrometer. The instrument is similar to that of the Smart-1 SIR. It was activated on 19 November 2008 and scientific observations were successfully started on 20 November 2008.
- **miniSAR**, designed, built and tested for NASA by a large team that includes the Naval Air Warfare Center, Johns Hopkins University Applied Physics Laboratory, Sandia National Laboratories, Raytheon and Northrop Grumman; it is the active Synthetic Aperture Radar system to search for lunar polar ice. The instrument transmitted right polarised radiation with a frequency of 2.5 GHz and

monitored scattered left and right polarised radiation. The Fresnel reflectivity and the circular polarisation ratio (CPR) are the key parameters deduced from these measurements. Ice shows the Coherent Backscatter Opposition Effect which results in an enhancement of reflections and CPR, so that water content of the Moon's polar regions can be estimated.

- **RADOM-7, Radiation Dose Monitor Experiment** from the Bulgarian Academy of Sciences maps the radiation environment around the Moon. It was successfully tested on 16 November 2008.

Space flight

Chandrayaan-1 was launched on 22 October 2008 at 6.22 am IST from Satish Dhawan Space Centre using the ISRO's 44.4 metre tall four-stage PSLV launch rocket.

Chandrayaan-1 was sent to the Moon in a series of orbit-increasing manoeuvres around the Earth over a period of 21 days as opposed to launching the craft on a direct trajectory to the Moon. At launch the spacecraft was inserted into geostationary transfer orbit (GTO) with an apogee of 22,860 km and a perigee of 255 km. The apogee was increased with a series of five orbit burns conducted over a period of 13 days after launch.

For the duration of the mission, ISRO's telemetry, tracking and command network (ISTRAC) at Peenya in Bangalore, tracked and controlled Chandrayaan-1. Scientists from India, Europe, and the U.S. conducted a high-level review of Chandrayaan-1 on 29 January 2009 after the spacecraft completed its first 100 days in space.

Earth orbit burns

First orbit burn

The first orbit-raising manoeuvre of Chandrayaan-1 spacecraft was performed at 09:00 hrs IST on 23 October 2008 when the spacecraft's 440 Newton Liquid Engine was fired for about 18 minutes by commanding the spacecraft from Spacecraft Control Centre (SCC) at ISRO Telemetry, Tracking and Command Network (ISTRAC) at Peenya, Bangalore. With this Chandrayaan-1's apogee was raised to 37,900 km, and its perigee to 305 km. In this orbit, Chandrayaan-1 spacecraft took about 11 hours to go around the Earth once.

Second orbit burn

The second orbit-raising manoeuvre of Chandrayaan-1 spacecraft was carried out on 25 October 2008 at 05:48 IST when the spacecraft's engine was fired for about 16 minutes, raising its apogee to 74,715 km, and its perigee to 336 km, thus completing 20 percent of its journey. In this orbit, Chandrayaan-1 spacecraft took about twenty-five and a half hours to go round the Earth once. This is the first time an Indian spacecraft has gone beyond the 36,000 km high geostationary orbit and reached an altitude more than twice that height.

Third orbit burn

The third orbit raising manoeuvre was initiated on 26 October 2008 at 07:08 IST when the spacecraft's engine was fired for about nine and a half minutes. With this its apogee was raised to 164,600 km, and the perigee to 348 km. In this orbit, Chandrayaan-1 took about 73 hours to go around the Earth once.

Fourth orbit burn

The fourth orbit-raising maneuver took place on 29 October 2008 at 07:38 IST when the spacecraft's engine was fired for about three minutes, raising its apogee to 267,000 km and the perigee to 465 km. This extended its orbit to a distance more than half the way to the Moon. In this orbit, the spacecraft took about six days to go around the Earth once.

Final orbit burn

The fifth and final orbit raising manoeuvre was carried out on 4 November 2008 04:56 am IST when the spacecraft's engine was fired for about two and a half minutes resulting in Chandrayaan-1 entering the Lunar Transfer Trajectory with an apogee of about 380,000 km.

Lunar orbit insertion

Chandrayaan-1 successfully completed the lunar orbit insertion operation on 8 Nov 2008 at 16:51 IST. This manoeuvre involved firing of the liquid engine for 817 seconds (about thirteen and half minutes) when the spacecraft passed within 500 km from the Moon. The satellite was placed in an elliptical orbit that passed over the polar regions of the Moon, with 7502 km aposelene (point farthest away from the Moon) and 504 km periselene (nearest to the Moon). The orbital period was estimated to be around 11 hours. With the successful completion of this operation, India became the fifth nation to put a vehicle in lunar orbit.

First orbit reduction

First Lunar Orbit Reduction Manoeuvre of Chandrayaan-1 was carried out successfully on 9 November 2008 at 20:03 IST. During this, the engine of the spacecraft was fired for about 57 seconds. This reduced the periselene from 504 km to 200 km while aposelene remained unchanged at 7,502 km. In this elliptical orbit, Chandrayaan-1 took about ten and a half hours to circle the Moon once.

Second orbit reduction

This manoeuvre, which resulted in steep decrease in Chandrayaan-1's aposelene from 7,502 km to 255 km and its periselene from 200 km to 187 km, was carried out on 10 November 2008 at 21:58 IST. During this manoeuvre, the engine was fired for about

866 seconds (about fourteen and half minutes). Chandrayaan-1 took two hours and 16 minutes to go around the Moon once in this orbit.

Third orbit reduction

Third Lunar Orbit Reduction was carried out by firing the on board engine for 31 seconds on 11 November 2008 at 18:30 IST. This reduced the periselene from 187 km to 101 km, while the aposelene remained constant at 255 km. In this orbit Chandrayaan-1 took two hours and 9 minutes to go around the Moon once.

Final orbit

Chandrayaan-1 spacecraft was successfully placed into a mission-specific lunar polar orbit of 100 km above the lunar surface on 12 November 2008. In the final orbit reduction manoeuvre, Chandrayaan-1's aposelene was reduced from 255 km to 100 km while the periselene was reduced from 101 km to 100 km. In this orbit, Chandrayaan-1 takes about two hours to go around the Moon once. Two of the 11 payloads – the Terrain Mapping Camera (TMC) and the Radiation Dose Monitor (RADOM) – have already been successfully switched on. The TMC successfully acquired images of both the Earth and the Moon.

Impact of the MIP on the lunar surface

The Moon Impact Probe (MIP) crash-landed on the lunar surface on 14 November 2008, 15:01 UTC (20:31 Indian Standard Time (IST)) near the crater Shackleton at the south pole. The MIP was one of eleven scientific instruments (payloads) on board Chandrayaan-1.

The MIP separated from Chandrayaan at 100 km from lunar surface and began its nosedive at 14:36 UTC (20:06 IST). going into free fall for thirty minutes. As it fell, it kept sending information back to the mother satellite which, in turn, beamed the information back to Earth. The altimeter then also began recording measurements to prepare for a rover to land on the lunar surface during a second Moon mission - planned for 2012.

Following the successful deployment of the MIP, the other scientific instruments were turned on, starting the next phase of the mission.

After scientific analyses of the received data from the MIP, the Indian Space Research Organisation confirmed the presence of water in the lunar soil and published the finding in a press conference addressed by its then Chairman Sri. G. Madhavan Nair.

Rise of spacecraft's temperature

ISRO had reported on 25 November 2008 that Chandrayaan-1's temperature had risen above normal to 50 °C, scientists said that it was caused by higher than normal

temperatures in lunar orbit. The temperature was brought down by about 10 °C by rotating the spacecraft about 20 degrees and switching off some of the instruments. Subsequently ISRO reported on 27 November 2008 that the spacecraft was operating under normal temperature conditions. In subsequent reports ISRO says, since the spacecraft was still recording higher than normal temperatures, it would be running only one instrument at a time until January 2009 when lunar orbital temperature conditions are said to stabilise. The spacecraft was experiencing high temperature because of radiation from the Sun and infrared radiation reflected by the Moon.

Mapping of minerals

The mineral content on the lunar surface was mapped with the Moon Mineralogy Mapper (M³), a NASA instrument on board the orbiter. The presence of iron was reiterated and changes in rock and mineral composition have been identified. The Oriental Basin region of the Moon was mapped, and it indicates abundance of iron-bearing minerals such as pyroxene.

Mapping of Apollo landing sites

ISRO claims that the landing sites of the Apollo Moon missions have been mapped by the orbiter using multiple payloads. Six of the sites have been mapped including that of Apollo 11, the first mission that brought humans on the Moon.

Images acquisition

The craft completed 3000 orbits acquiring 70000 images of the lunar surface, which many in ISRO believe is quite a record compared to the lunar flights of other nations. ISRO officials estimated that if more than 40,000 images have been transmitted by Chandrayaan's cameras in 75 days, it worked out to nearly 535 images being sent daily. They were first transmitted to Indian Deep Space Network at Byalalu near Bangalore, from where they were flashed to ISRO's Telemetry Tracking And Command Network (ISTRAC) at Bangalore.

Some of these images have a resolution of up to 5 metres, providing a sharp and clear picture of the Moon's surface, while many images sent by some of the other missions had a 100-metre resolution.

On 26 November, the indigenous Terrain Mapping Camera, which was first activated on 29 October 2008, acquired images of peaks and craters. This came as a surprise to ISRO officials because the Moon consists mostly of craters.

Detection of X-Ray signals

The X-ray signatures of aluminium, magnesium and silicon were picked up by the C1XS X-ray camera. The signals were picked up during a solar flare that caused an X-ray

fluorescence phenomenon. The flare that caused the fluorescence was within the lowest C1XS sensitivity range.

Full Earth image

On 25 March 2009 Chandrayaan beamed back its first images of the Earth in its entirety. These images were taken with the TMC. Previous imaging was done on only part of the Earth. The new images show Asia, parts of Africa and Australia with India being in the center.

Chapter- 9

Space and Solar System Exploration in 2009

Lunar Reconnaissance Orbiter

Lunar Reconnaissance Orbiter



LRO spacecraft, artist's rendering

Operator	NASA/Goddard Space Flight Center
Mission type	Orbiter
Satellite of	Earth's Moon
Orbits	30–70 km polar orbit, extended mission 30–216 km
Launch date	18 June 2009 21:32:00 UTC
Launch vehicle	Atlas V 401
Launch site	Space Launch Complex 41 Cape Canaveral Air Force Station
Mission duration	one year, extended mission of up to five years elapsed: 1 year, 6 months, and 29 days

COSPAR ID 2009-031A

Mass 1,846 kg

Power 1,850 W

The **Lunar Reconnaissance Orbiter (LRO)** is a NASA robotic spacecraft currently (as of April 2010) orbiting the Moon on a low 50 km polar mapping orbit. The LRO mission is a precursor to future manned missions to the moon by NASA. To this end a detailed mapping program will identify safe landing sites, locate potential resources on the moon, characterize the radiation environment, and demonstrate new technology.

The probe will make a 3-D map of the Moon's surface and has provided some of the first images of Apollo equipment left on the Moon. The first images from LRO were published on 2 July 2009, showing a region in the lunar highlands south of Mare Nubium (*Sea of Clouds*).

Launched on 18 June 2009, in conjunction with the Lunar Crater Observation and Sensing Satellite (LCROSS), as the vanguard of NASA's Lunar Precursor Robotic Program, this is the first United States mission to the Moon in over ten years. LRO and LCROSS are the first missions launched as part of the United States's Vision for Space Exploration program.

The total cost of the mission is reported as US\$583 million, of which \$504 million pertains to the main LRO probe and \$79 million to the LCROSS satellite.

Mission

Developed at NASA's Goddard Space Flight Center, LRO is a large (1,900 kg) and sophisticated spacecraft planned to fly in a lunar polar orbit for a mission of one Earth year. An optional extended phase of the mission (up to five years) could provide a communications relay for future lunar ground missions, such as a Moon lander or rover.

After completing a preliminary design review in February 2006 and a critical design review in November 2006, the LRO was shipped from Goddard Space Flight Center to Cape Canaveral Air Force Station on 11 February 2009. Launch was planned for October 2008, but this slid to April as the spacecraft underwent testing in a thermal vacuum chamber. Launch was rescheduled for June 17, 2009 because of the delay in a priority military launch, and happened one day later, on June 18. The one-day delay was to allow the Space Shuttle Endeavour a chance to lift off for mission STS-127 following a hydrogen fuel leak that canceled an earlier planned launch.

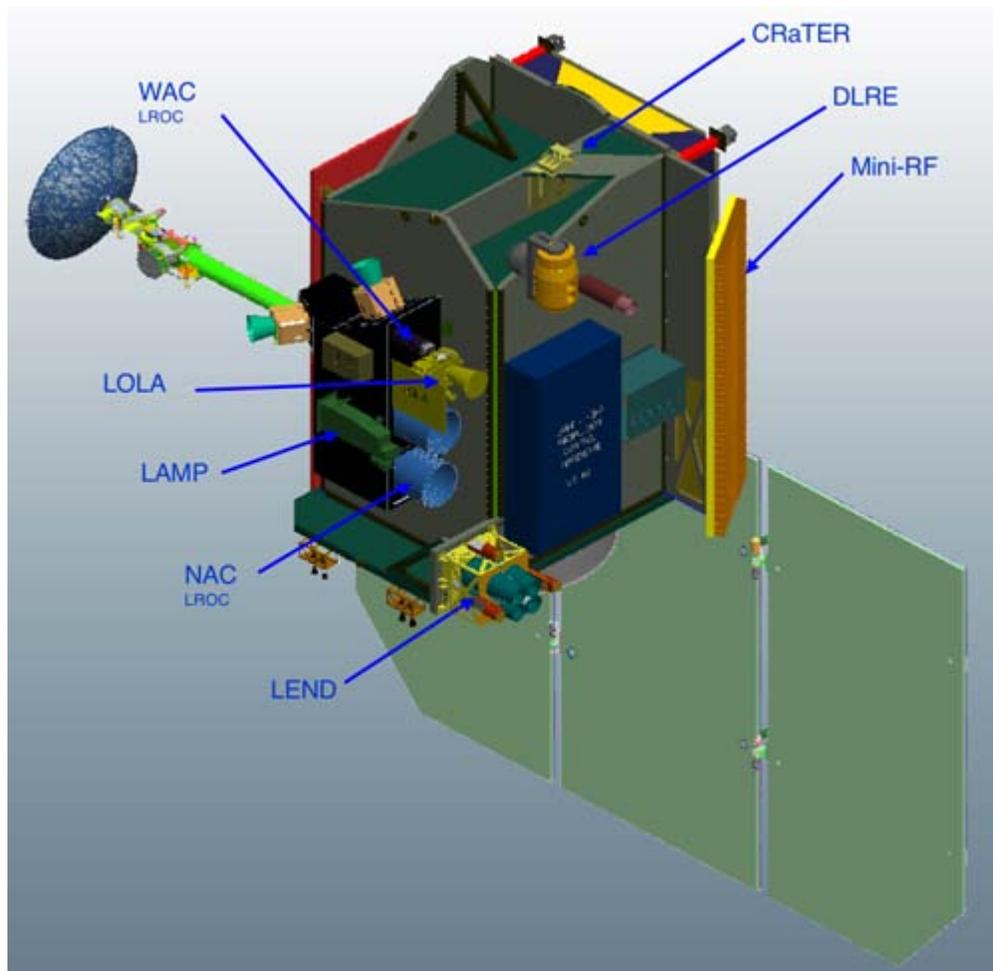
Areas of investigation will include:

- Selenodetic global topography.
- Characterization of deep space radiation in lunar orbit.

- The lunar polar regions, including possible water ice deposits and the lighting environment. The lunar polar regions experience temperatures of $-223\text{ }^{\circ}\text{C}$ ($-369.4\text{ }^{\circ}\text{F}$) and may be able to hold water ice.
- High-resolution mapping (max 0.5 metres (1.6 ft)) to assist in the selection and characterization of future landing sites.

In addition, LRO has provided some of the first images of leftover Apollo equipment on the Moon.

Payload



Onboard instruments

The orbiter carries a complement of six instruments and one technology demonstration:

- **CRaTER**—The primary goal of the **Cosmic Ray Telescope for the Effects of Radiation** is to characterize the global lunar radiation environment and its biological impacts.

- **DLRE**—The **D**iviner **L**unar **R**adiometer **E**xperiment will measure lunar surface thermal emission to provide information for future surface operations and exploration.
- **LAMP**—The **L**yman-**A**lpha **M**apping **P**roject will peer into permanently shadowed craters in search of water ice, seeing by the ultraviolet light from stars and the interplanetary medium.
- **LEND**—The **L**unar **E**xploration **N**eutron **D**etector will provide measurements, create maps, and detect possible near-surface water ice deposits.
- **LOLA**—The **L**unar **O**rbiter **L**aser **A**ltimeter investigation will provide a precise global lunar topographic model and geodetic grid.
- **LROC**—The **L**unar **R**econnaisance **O**rbiter **C**amera has been designed to address the measurement requirements of landing site certification and polar illumination. LROC comprises a pair of narrow-angle cameras (NAC) and a single wide-angle camera (WAC). LROC will fly several times over the historic Apollo lunar landing sites at 31 miles (50 km) altitude; with the camera's high resolution, the lunar rovers and Lunar Module descent stages and their respective shadows will be clearly visible, along with other equipment previously left on the Moon. The mission will return approximately 70–100 Terabytes of image data. It is expected that this photography will boost public acknowledgement of the validity of the landings, and further discredit Apollo conspiracy theories.
- **Mini-RF**—The **M**iniature **R**adio **F**requency radar will demonstrate new lightweight SAR and communications technologies and locate potential water-ice.

Names to the Moon



The microchip panel containing 1.6 million names

Prior to the LRO's launch, NASA gave members of the public the opportunity to have their names placed in a microchip on the LRO. The deadline for this opportunity was 31 July 2008. About 1.6 million names were submitted.

Mission progress



In this image, the lower of the two green beams is from the Lunar Reconnaissance Orbiter's dedicated tracker.

On June 23, 2009, the Lunar Reconnaissance Orbiter entered into orbit around the Moon after a four and a half day journey from the Earth. When launched, the spacecraft was aimed at a point ahead of the Moon's position. A mid-course correction was required during the trip in order for the spacecraft to correctly enter Lunar orbit. Once the spacecraft reached the far side of the Moon, its rocket motor was fired in order for it to be captured by the Moon's gravity into an elliptical lunar orbit. A series of four rocket burns over the next four days put the satellite into its commissioning phase orbit where each instrument was brought online and tested. On September 15, 2009, the spacecraft started its primary mission by orbiting the Moon at about 50 kilometers (31 mi) for one year.

On August 21, 2009, the spacecraft, along with the Chandrayaan-1, was used to perform a Bistatic radar experiment to detect the presence of water ice on the lunar surface. In this

experiment, Chandrayaan transmitted radar pulses which, after reflection from the surface, were picked up by the receivers of LRO and in a different angle by the Chandrayaan. Both receivers, Mini-RF in LRO and Mini-SAR in Chandrayaan, are similar in nature. They were pointed at the Erlanger crater for four minutes during which the observations were made.

NASA's LCROSS mission culminated with two lunar impacts at approximately 4:30 a.m. PDT on October 9. The goal of the impact was the search for water in the Cabeus crater near the Moon's south pole, and preliminary results indicated the presence of both water and hydroxyl, an ion related to water.

On December 17, 2010, the topographic map of the Moon based on data gathered by the LOLA instrument was released to the public. This is the most accurate topographic map of the Moon to date.