Spacecraft Missions to Asteroids

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Galileo (Spacecraft)

Galileo Orbiter

Galileo is prepared for mating with the IUS booster

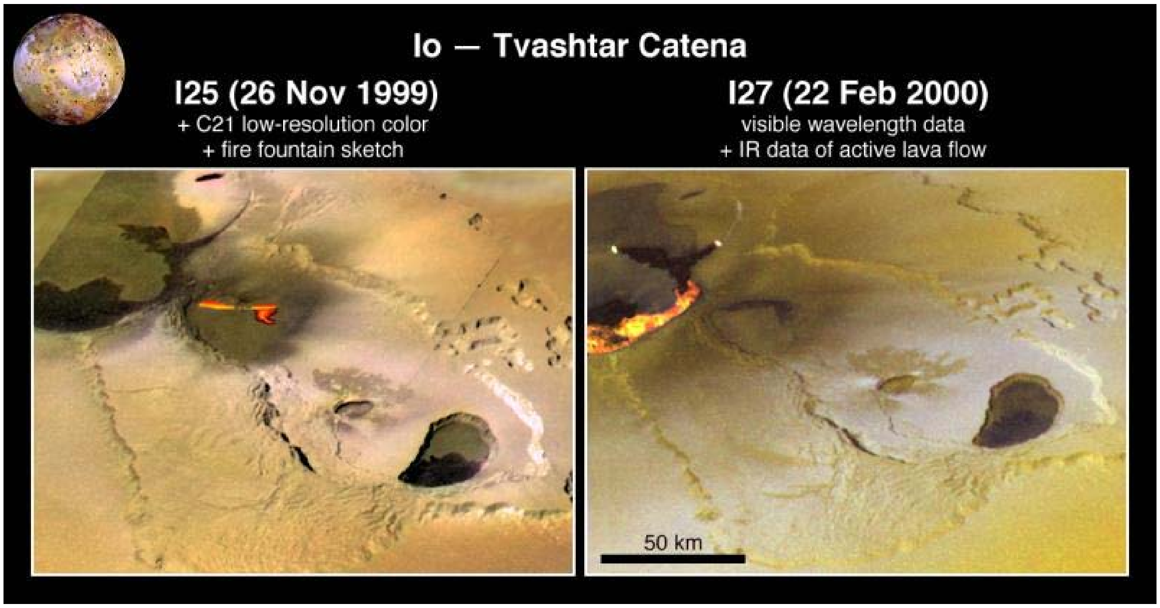
Operator	NASA
Mission type	Orbiter, Fly-by
Flyby of	Venus, Earth, 951 Gaspra, 243 Ida
Satellite of	**Jupiter**
Orbital insertion date	1995-12-08 01:20:00 UTC
Launch date	1989-10-18 16:53:00 UTC
Launch vehicle	Space Shuttle Atlantis Inertial Upper Stage
Launch site	KSC Launch Complex 39B Kennedy Space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

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

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

Galileo and Inertial Upper Stage in space

The four largest moons of Jupiter photographed by *Galileo*



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

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

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

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

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

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

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

Mission overview

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

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

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

The *Galileo* spacecraft

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

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

Command and data handling

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

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

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

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

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

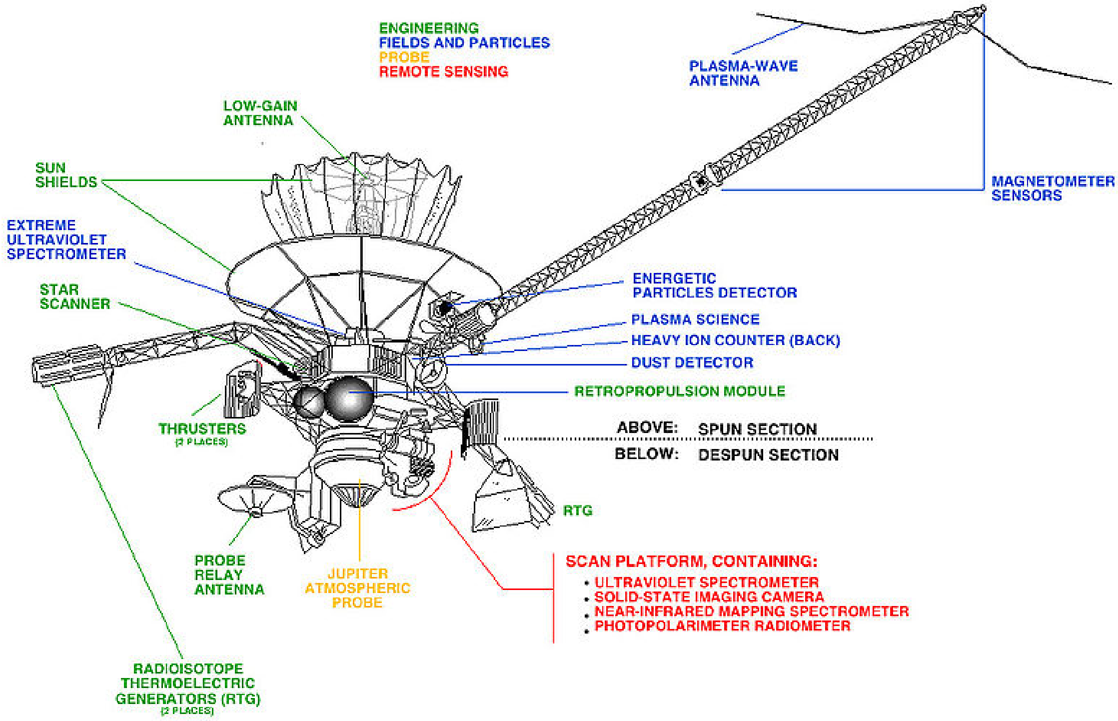
Propulsion

The Propulsion Subsystem consisted of a 400 N main engine and twelve 10 N thrusters together with propellant, storage and pressurizing tanks, and associated plumbing. The 10 N thrusters were mounted in groups of six on two 2-meter booms. The fuel for the system was 925 kg of monomethylhydrazine and nitrogen tetroxide. Two separate tanks held another 7 kg of helium pressurant. The Propulsion Subsystem was developed and built by Daimler Benz Aero Space AG (DASA) (formerly Messerschmitt–Bölkow–Blohm (MBB)) and provided by Germany, the major international partner in Project *Galileo*.

Electrical power

Solar panels were not a practical solution for *Galileo*'s power needs at Jupiter's distance from the Sun (it would have needed a *minimum* of 65 square metres (700 ft^2) of solar panels); as for batteries, they would have been prohibitively massive. The solution adopted consisted of two radioisotope thermoelectric generators (RTGs). The RTGs powered the spacecraft through the radioactive decay of plutonium-238. The heat emitted by this decay was converted into electricity for the spacecraft through the solid-state Seebeck effect. This provided a reliable and long-lasting source of electricity unaffected by the cold space environment and high radiation fields such as those encountered in Jupiter's magnetosphere.

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



Overview of *Galileo*'s components

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

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

Instrumentation overview

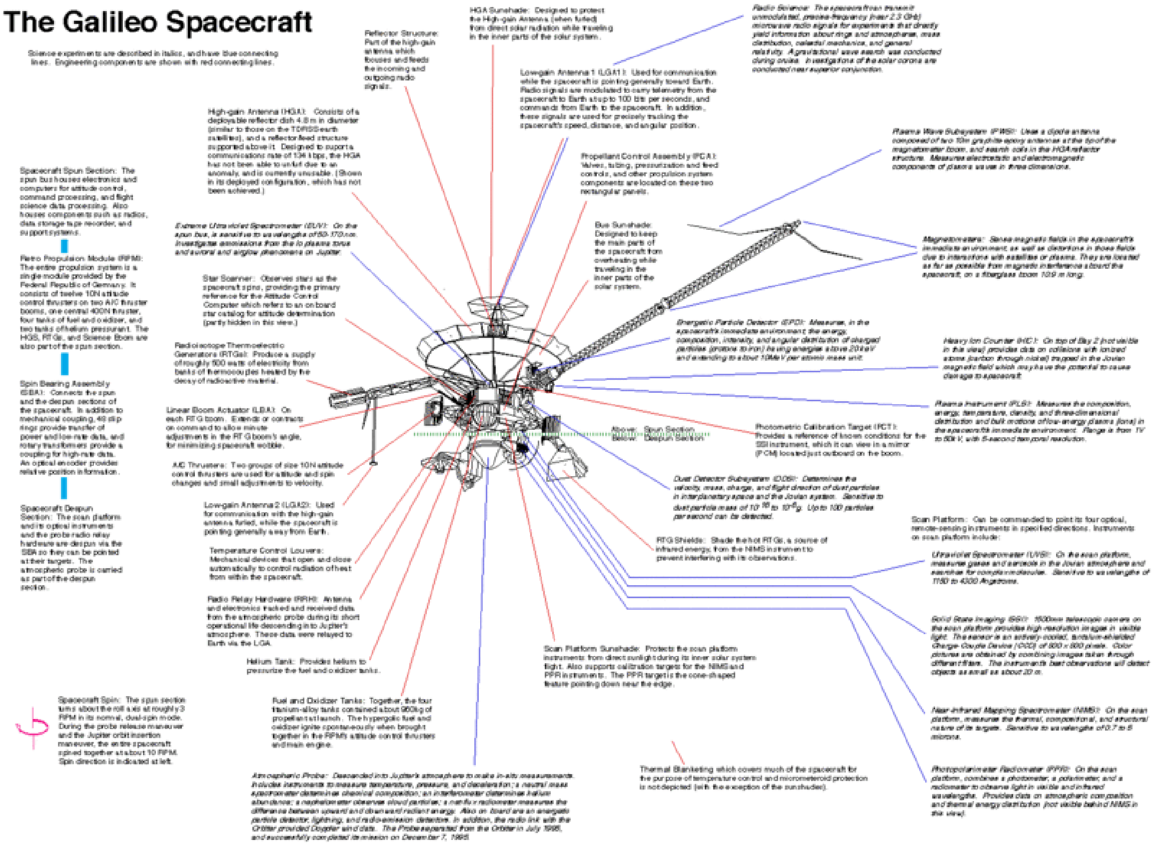
Scientific instruments to measure fields and particles were mounted on the spinning section of the spacecraft, together with the main antenna, power supply, the propulsion module and most of the *Galileo* computers and control electronics. The sixteen instruments, weighing 118 kg altogether, included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

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

Instrumentation details

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

Despun section



Highly detailed diagram of *Galileo* instruments and subsystems.

Solid-State Imaging camera of the Galileo spacecraft

Solid State Imager (SSI)

The SSI is an 800 by 800 pixel solid state camera consisting of an array of silicon sensors called a "charge coupled device" (CCD). Galileo was one of the first spacecraft to be equipped with CCD camera. The optical portion of the camera is built as a Cassegrain telescope. Light is collected by the primary mirror and directed to a smaller secondary mirror that channels it through a hole in the center of the primary mirror and onto the CCD. The CCD sensor is shielded from radiation, a particular problem within the harsh Jovian magnetosphere. The shielding is accomplished by means of a 10 mm thick layer of tantalum surrounding the CCD except where the light enters the system. An eight position filter wheel is used to obtain images at specific wavelengths. The images are then combined electronically on Earth to produce color images. The spectral response of the SSI ranges from about 0.4 to 1.1 micrometres. The SSI weighs 29.7 kilograms and consumes, on average, 15 watts of power.

Near-Infrared Mapping Spectrometer (NIMS)

The NIMS instrument is sensitive from 0.7 to 5.2 micrometre wavelength IR light, overlapping the wavelength range of SSI. The telescope associated with NIMS is all reflective (uses mirrors and no lenses) with an aperture of 229 mm. The spectrometer of NIMS uses a grating to disperse the light collected by the telescope. The dispersed spectrum of light is focused on detectors of indium antimonide and silicon. The NIMS weighs 18 kilograms and uses 12 watts of power on average.

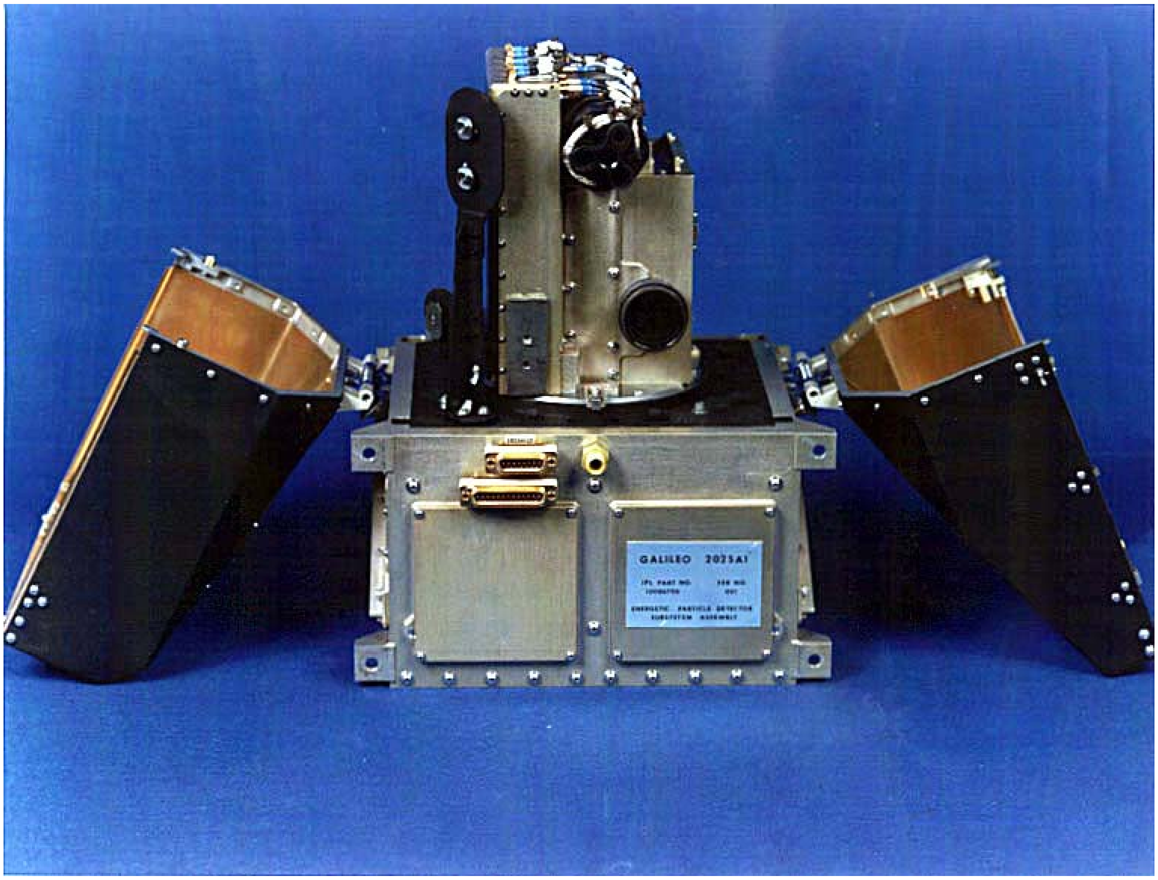
Ultraviolet Spectrometer / Extreme Ultraviolet Spectrometer (UVS/EUV)

The Cassegrain telescope of the UVS has a 250 mm aperture and collects light from the observation target. Both the UVS and EUV instruments use a ruled grating to disperse this light for spectral analysis. This light then passes through an exit slit into photomultiplier tubes that produce pulses or "sprays" of electrons. These electron pulses are counted, and these count numbers are the data that are sent to Earth. The UVS is mounted on the scan platform and can be pointed to an object in inertial space. The EUV is mounted on the spun section of the spacecraft. As *Galileo* spins, the EUV observes a narrow ribbon of space perpendicular to the spin axis. The two instruments combined weigh about 9.7 kilograms and use 5.9 watts of power.

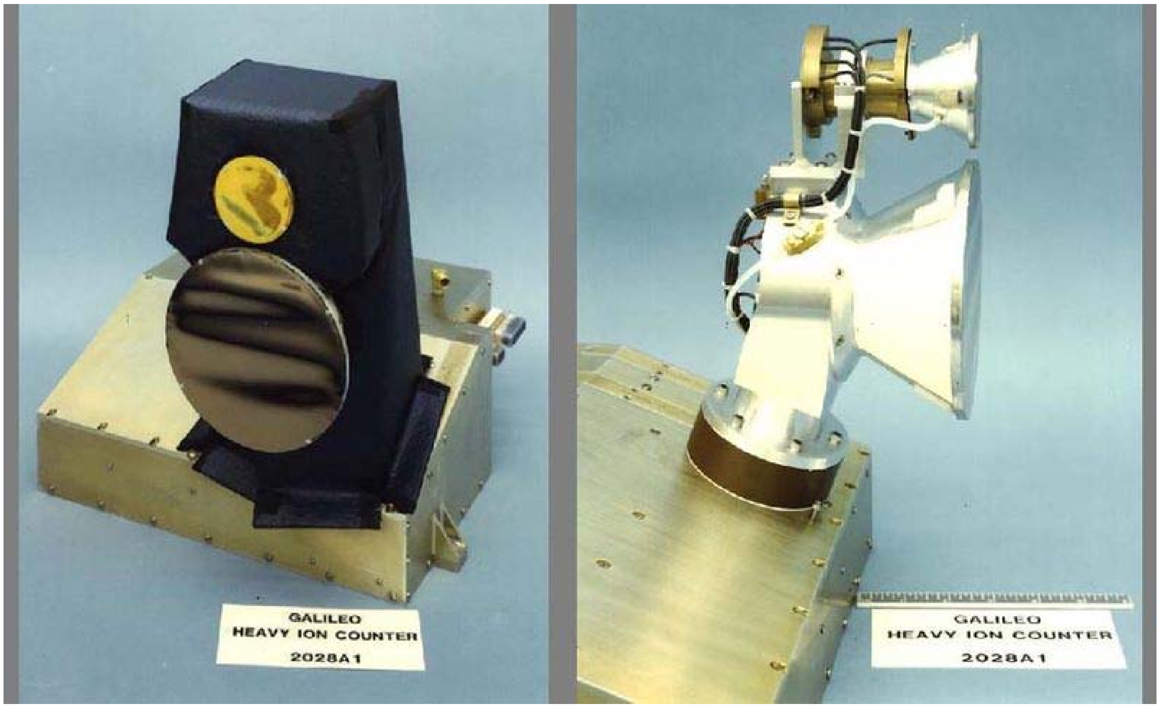
Photopolarimeter-Radiometer (PPR)

The PPR has seven radiometry bands. One of these uses no filters and observes all the radiation, both solar and thermal. Another band lets only solar radiation through. The difference between the solar- plus-thermal and the solar-only channels gives the total thermal radiation emitted. The PPR also measured in five broadband channels that span the spectral range from 17 to 110 micrometres. The radiometer provides data on the temperatures of the Jovian satellites and Jupiter's atmosphere. The design of the instrument is based on that of an instrument flown on the Pioneer Venus spacecraft. A 100 mm aperture reflecting telescope collects light, directs it to a series of filters, and, from there, measurements are performed by the detectors of the PPR. The PPR weighs 5.0 kilograms and consumes about 5 watts of power.

Spun section



Energetic Particles Detector of the Galileo spacecraft



Heavy Ion Counter of the Galileo spacecraft

Dust Detector Subsystem (DDS)

The Dust Detector Subsystem (DDS) was used to measure the mass, electric charge, and velocity of incoming particles. The masses of dust particles that the DDS can detect go from 10^{-16} to 10^{-7} grams. The speed of these small particles can be measured over the range of 1 to 70 kilometers per second. The instrument can measure impact rates from 1 particle per 115 days (10 megaseconds) to 100 particles per second. These particles will help determine dust origin and dynamics within the magnetosphere. The DDS weighs 4.2 kilograms and uses an average of 5.4 watts of power.

Energetic Particles Detector (EPD)

The energetic particles detector (EPD) is designed to measure the numbers and energies of ions and electrons whose energies exceed about 20 keV (3.2 fJ). The EPD can also measure the direction of travel of such particles and, in the case of ions, can determine their composition (whether the ion is oxygen or sulfur, for example). The EPD uses silicon solid state detectors and a time-of-flight detector system to measure changes in the energetic particle population at Jupiter as a function of position and time. These measurements will tell us how the particles get their energy and how they are transported through Jupiter's magnetosphere. The EPD weighs 10.5 kilograms and uses 10.1 watts of power on average.

Heavy Ion Counter (HIC)

The HIC is really a repackaged and updated version of some parts of the flight spare of the Voyager Cosmic Ray System. The HIC detects heavy ions using stacks of single crystal silicon wafers. The HIC can measure heavy ions with energies as low as 6 MeV (1 pJ) and as high as 200 MeV (32 pJ) per nucleon. This range includes all atomic substances between carbon and nickel. The HIC and the EUV share a communications link and, therefore, must share observing time. The HIC weighs 8 kilograms and uses an average of 2.8 watts of power.

Magnetometer (MAG)

The magnetometer (MAG) uses two sets of three sensors. The three sensors allow the three orthogonal components of the magnetic field section to be measured. One set is located at the end of the magnetometer boom and, in this position, is about 11 m from the spin axis of the spacecraft. The second set, designed to detect stronger fields, is 6.7 m from the spin axis. The boom is used to remove the MAG from the immediate vicinity of the spacecraft to minimize magnetic effects from the spacecraft. However, not all these effects can be eliminated by distancing the instrument. The rotation of the spacecraft is used to separate natural magnetic fields from engineering induced fields. Another source of potential error in measurement comes from bending and twisting of the long magnetometer boom. To account for these motions, a calibration coil is mounted rigidly on the spacecraft and puts out a reference magnetic field during calibrations. The magnetic field at the surface of the Earth has a strength of about 50,000 nT. At Jupiter, the outboard (11 m) set of sensors can measure magnetic field strengths in the range from ±32 to ±512 nT while the inboard (6.7 m) set is active in the range from ±512 to ±16,384 nT. The MAG experiment weighs 7 kilograms and uses 3.9 watts of power.

Plasma Subsystem (PLS)

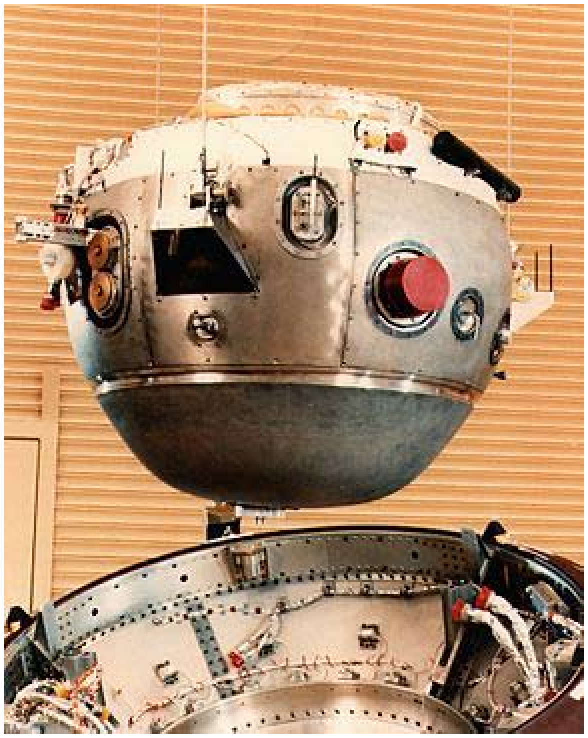
The PLS uses seven fields of view to collect charged particles for energy and mass analysis. These fields of view cover most angles from 0 to 180 degrees, fanning out from the spin axis. The rotation of the spacecraft carries each field of view through a full circle. The PLS will measure particles in the energy range from 0.9 eV to 52 keV (0.1 aJ to 8.3 fJ). The PLS weighs 13.2 kilograms and uses an average of 10.7 watts of power.

Plasma Wave Subsystem (PWS)

An electric dipole antenna is used to study the electric fields of plasmas, while two search coil magnetic antennas studied the magnetic fields. The electric dipole antenna is mounted at the tip of the magnetometer boom. The search coil magnetic antennas are mounted on the high-gain antenna feed. Nearly simultaneous measurements of the electric and magnetic field spectrum allowed electrostatic waves to be distinguished from electromagnetic waves. The PWS weighs 7.1 kilograms and uses an average of 9.8 watts.

Galileo's atmospheric entry probe

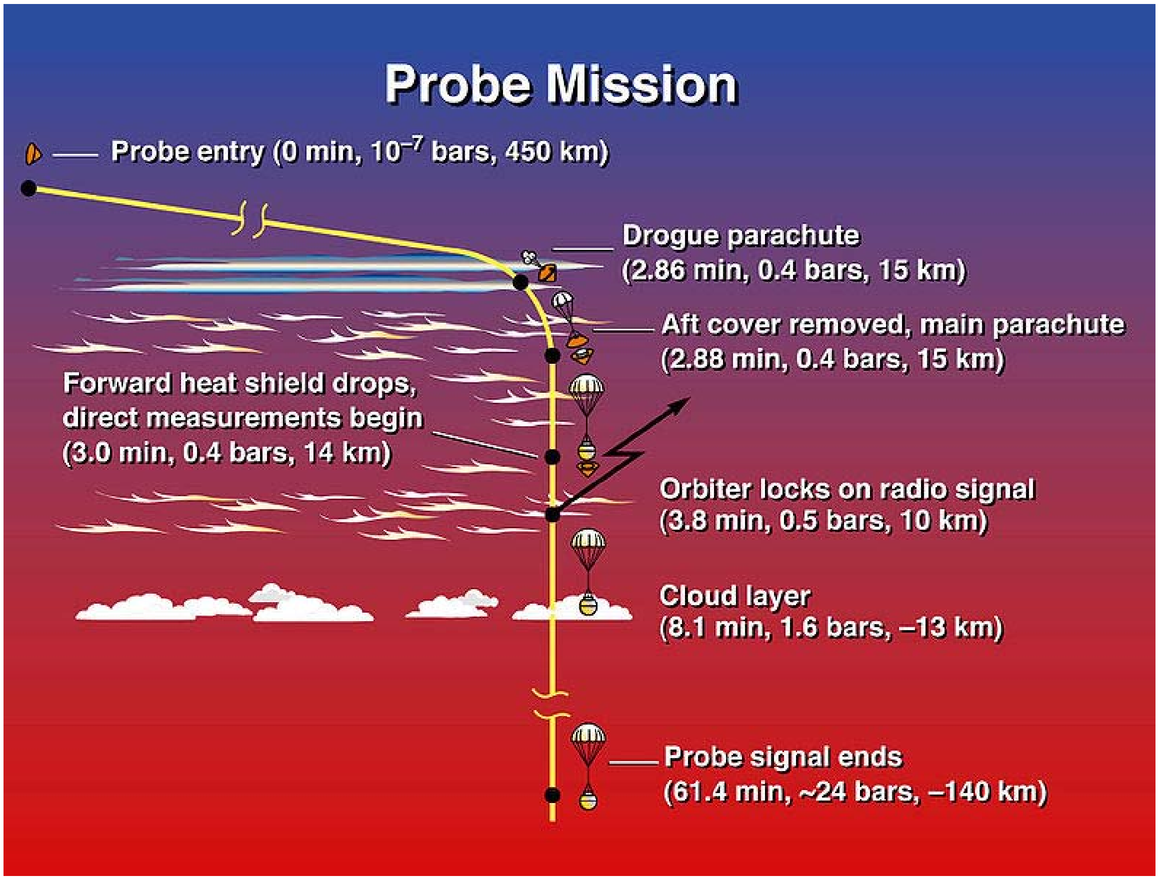
Galileo Probe



The *Galileo* Probe Descent Module

Operator	NASA
Mission type	Atmospheric probe
Launch date	July 13, 1995
Launch vehicle	Space Shuttle Atlantis Inertial Upper Stage Galileo Orbiter
Launch site	KSC Launch Complex 39B Kennedy Space Center
Mission duration	December 7, 1995 (57.6 minutes)
COSPAR ID	1989-084E
Homepage	*Galileo* Project Home Page
Mass	339 kg (750 lb)

Power	580 W ($LiSO_2$ battery)
Orbital elements	
Eccentricity	1.03116
Inclination	8.151°
Periapsis	0.9928 RJ



Timeline of probe atmospheric entry.

The 339 kilogram atmospheric probe, built by Hughes Aircraft Company at its El Segundo, California plant, measured about 1.3 meters across. Inside the heat shield, the scientific instruments were protected from ferocious heat during entry. The probe had to withstand extreme heat and pressure on its high speed journey at 47.8 km/s.

The probe was released from the main spacecraft in July 1995, five months before reaching Jupiter, and entered Jupiter's atmosphere with no braking beforehand. It was slowed from the probe's arrival speed of about 47 kilometers per second to subsonic speed in less than two minutes.

This was by far the most difficult atmospheric entry ever attempted; the probe had to withstand 230 g and the probe's 152 kg heat shield made up almost half of the probe's total mass, and lost 80 kg during the entry. NASA built a special laboratory, the Giant Planet Facility to simulate the heat load, which was similar to that of an ICBM-style straight-down reentry through a thermonuclear fireball. It then deployed its 2.5-meter (8 ft) parachute, and dropped its heat shield.

As the probe descended through 150 kilometers of the top layers of the atmosphere, it collected 58 minutes of data on the local weather. It only stopped transmitting when ambient pressure exceeded 23 atmospheres and temperature reached 153 °C (307 °F). The data was sent to the spacecraft overhead, then transmitted back to Earth. Each of 2 L-band transmitters operated at 128 bits per second and sent nearly identical streams of scientific data to the orbiter. All the probe's electronics were powered by lithium sulfur dioxide ($LiSO_2$) batteries that provided a nominal power output of about 580 watts with an estimated capacity of about 21 ampere-hours on arrival at Jupiter.

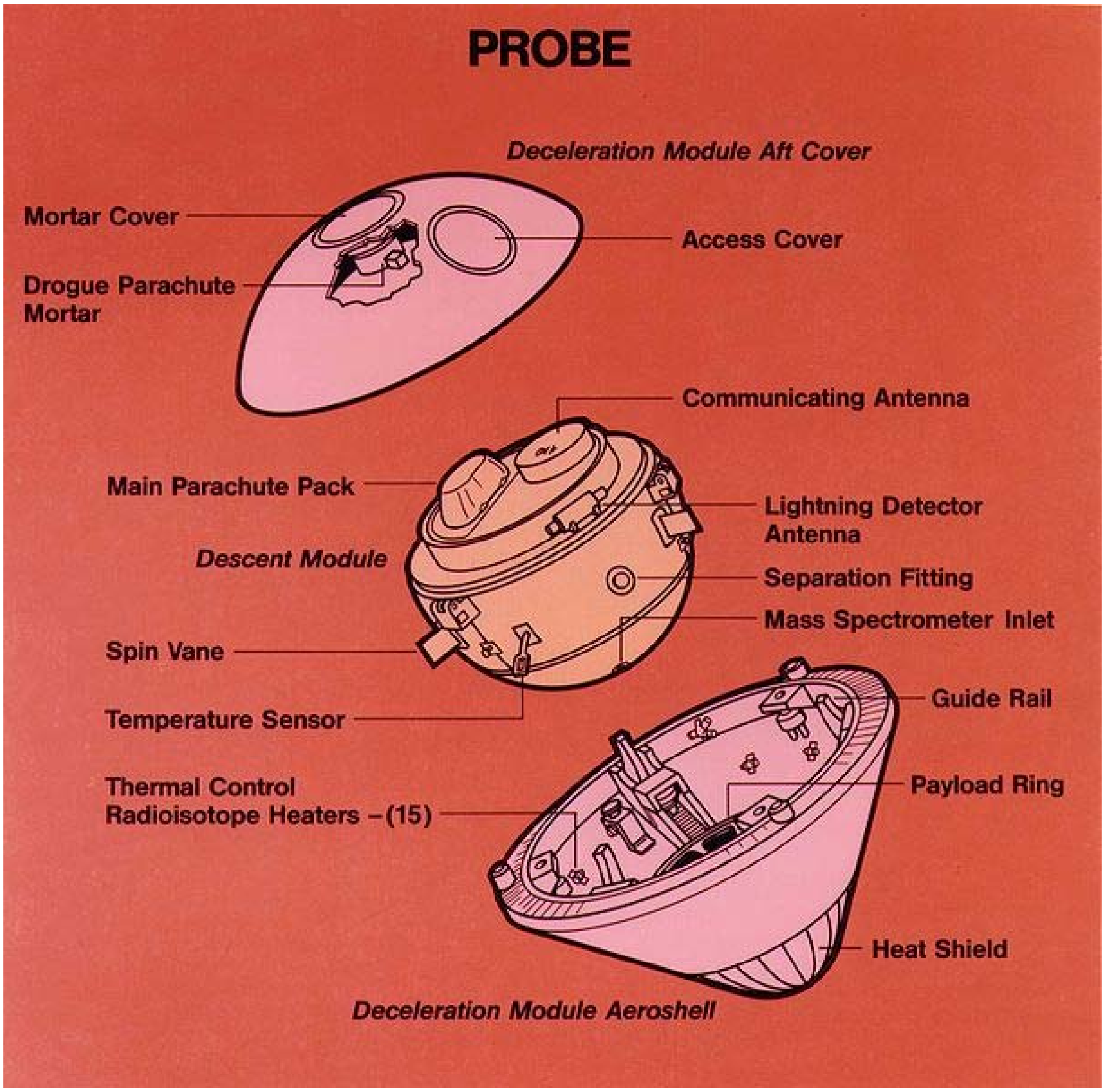


Diagram of *Galileo* atmospheric entry probe instruments and subsystems.

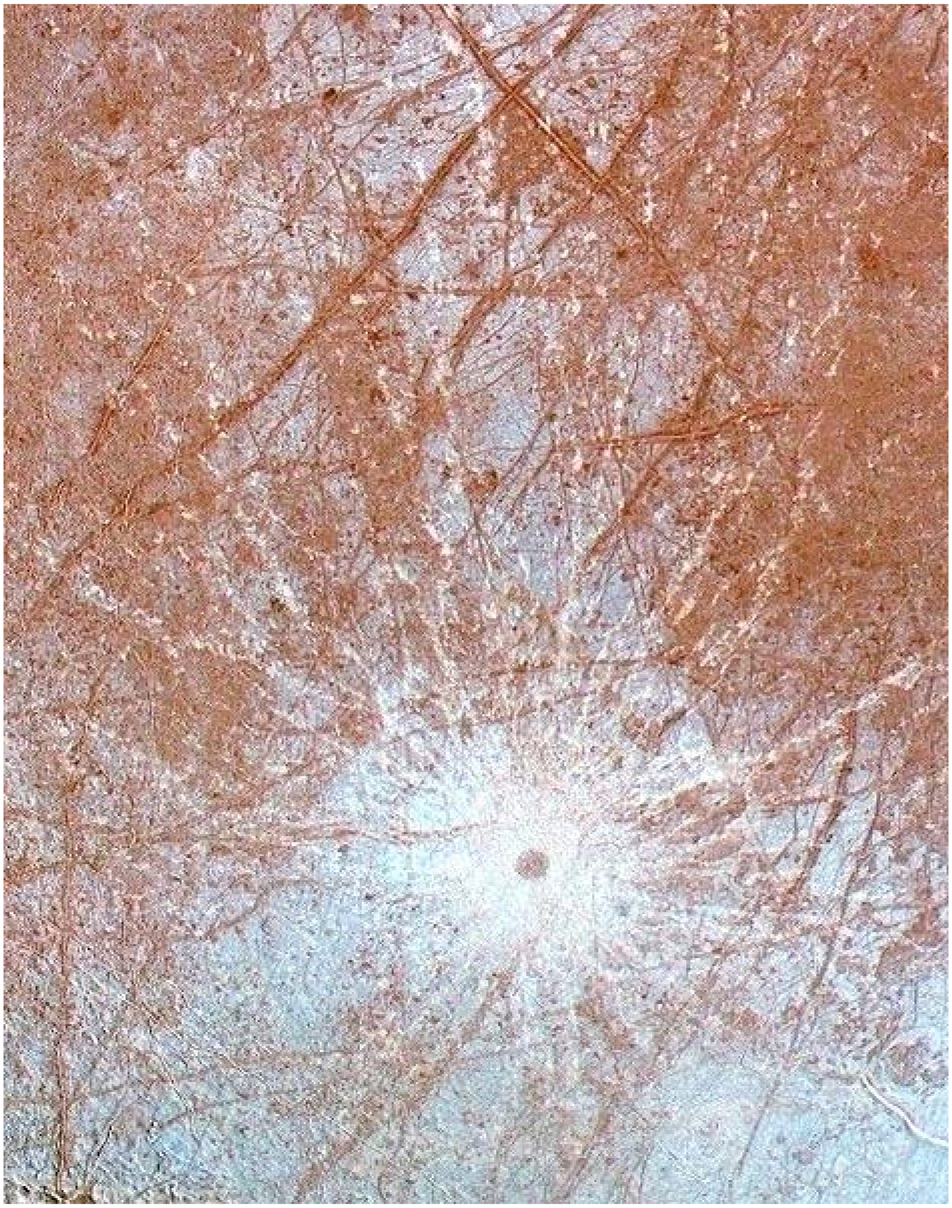
The probe included six instruments for taking data on its plunge into Jupiter:

- an *atmospheric structure instrument group* measuring temperature, pressure and deceleration,
- a *neutral mass spectrometer* and
- a *helium-abundance interferometer* supporting atmospheric composition studies,
- a *nephelometer* for cloud location and cloud-particle observations,
- a *net-flux radiometer* measuring the difference between upward and downward radiant flux at each altitude, and
- a *lightning/radio-emission instrument* with an energetic-particle detector that measured light and radio emissions associated with lightning and energetic particles in Jupiter's radiation belts.

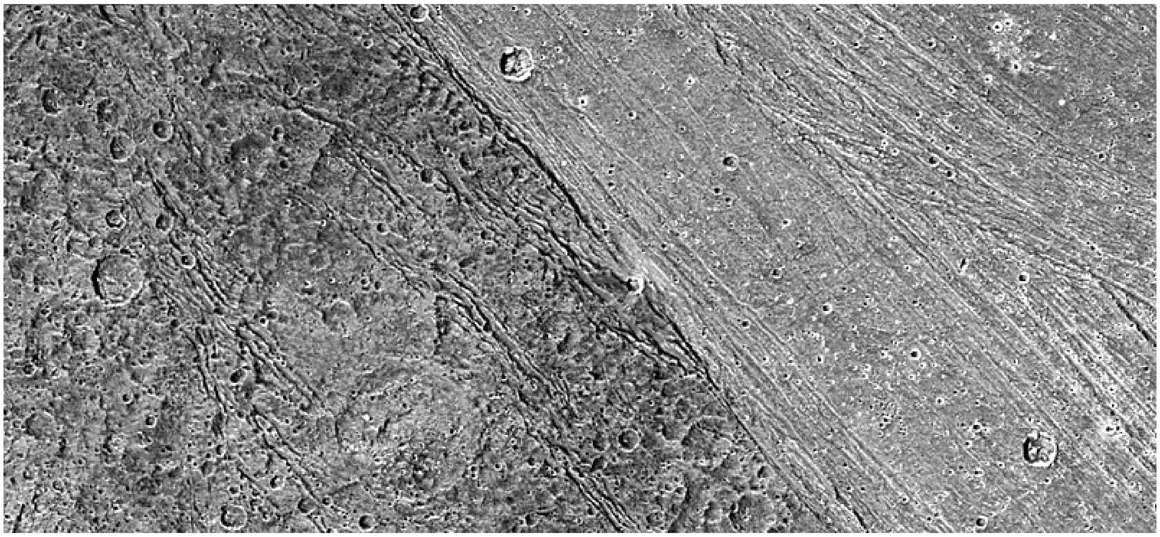
Total data returned from the probe was about 3.5 megabits (~458752 bytes). The probe stopped transmitting before the line of sight link with the orbiter was cut. The likely proximal cause of the final probe failure was overheating, which sensors indicated before signal loss.

The atmosphere through which the probe descended was somewhat more turbulent and hotter than expected. The probe was eventually completely destroyed as it continued to descend. The parachute would have melted first, roughly 30 minutes later, then the aluminum components after another 40 minutes of free fall. The titanium structure would have lasted 6.5 hours more before disintegrating. Due to the high pressure, the droplets of metals from the probe would finally have vaporised once their critical temperature had been reached, and mixed with Jupiter's liquid metallic hydrogen interior.

Science performed by the *Galileo* Orbiter at Jupiter



Pwyll crater on Europa



Terrain on Ganymede

After arriving on December 7, 1995 and completing 35 orbits around Jupiter throughout a nearly eight year mission, the *Galileo* Orbiter was destroyed during a controlled impact with Jupiter on September 21, 2003. During that intervening time, *Galileo* forever changed the way scientists saw Jupiter and provided a wealth of information on the moons orbiting the planet which will be studied for years to come. Culled from NASA's press kit, the top orbiter science results were:

- *Galileo* made the first observation of ammonia clouds in another planet's atmosphere. The atmosphere creates ammonia ice particles from material coming up from lower depths.
- The moon Io was confirmed to have extensive volcanic activity that is 100 times greater than that found on Earth. The heat and frequency of eruptions are reminiscent of early Earth.
- Complex plasma interactions in Io's atmosphere create immense electrical currents which couple to Jupiter's atmosphere.
- Several lines of evidence from *Galileo* support the theory that liquid oceans exist under Europa's icy surface.
- Ganymede possesses its own, substantial magnetic field - the first satellite known to have one.
- *Galileo* magnetic data provide evidence that Europa, Ganymede and Callisto have a liquid-saltwater layer under the visible surface.
- Evidence exists that Europa, Ganymede, and Callisto all have a thin atmospheric layer known as a 'surface-bound exosphere'.
- Jupiter's ring system is formed by dust kicked up as interplanetary meteoroids smash into the planet's four small inner moons. The outermost ring is actually two rings, one embedded with the other. There is probably a separate ring along Amalthea's orbit, as well.
- The *Galileo* spacecraft identified the global structure and dynamics of a giant planet's magnetosphere.

Other science conducted with *Galileo*

The *Galileo* star scanner

The star scanner was a small optical telescope used to provide the spacecraft with an absolute attitude reference. It was also able serendipitously to make scientific discoveries. In the prime mission, it was found that the star scanner was able to detect high energy particles as a noise signal. These data were eventually calibrated to show the particles were predominantly > 2 MeV electrons that were trapped in the Jovian magnetic belts.

A second discovery occurred in 2000. The star scanner was observing a set of stars which included the second magnitude star Delta Velorum. At one point, this star dimmed for 8 hours below the star scanner's detection threshold. Subsequent analysis of *Galileo* data and work by amateur and professional astronomers showed that Delta Velorum is the brightest known eclipsing binary, brighter at maximum than even Algol. It has a primary period of 45 days and the dimming is just visible with the naked eye.

A final discovery occurred during the last two orbits of the mission. When the spacecraft passed the orbit of Jupiter's moon Amalthea, the star scanner detected unexpected flashes of light that were reflections from moonlets. None of the individual moonlets were sighted twice, hence no orbits were determined and the moonlets did not meet the International Astronomical Union requirements to receive designations. It is believed that these moonlets most likely are debris ejected from Amalthea and form a tenuous, and perhaps temporary, ring.

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

Remote detection of life

The late Carl Sagan, pondering the question of whether life on Earth could be easily detected from space, devised a set of experiments in the late 1980s using *Galileo*'s remote sensing instruments to determine if life indeed could be detected during the first Earth flyby of the mission in December 1990. After data acquisition and processing, Sagan et al. published a paper in *Nature* in 1993 detailing the results of the experiment. *Galileo* had found what are now referred to as the "Sagan criteria for life"; these were: strong absorption of light at the red end of the visible spectrum (especially over continents) which was caused by absorption by chlorophyll in photosynthesizing plants, absorption bands of molecular oxygen which is also a result of plant activity, infrared absorption bands caused by the ~1 micromole per mole (µmol/mol) of methane in Earth's atmosphere (a gas which must be replenished by either volcanic or biological activity) and modulated narrowband radio wave transmissions uncharacteristic of any known natural source. *Galileo*'s experiments were thus the first ever controls in the newborn science of astrobiological remote sensing.

The *Galileo* optical experiment

In December 1992 during *Galileo*'s second gravity assist flyby of Earth, another groundbreaking yet almost entirely unpublicized experiment was done using *Galileo* to assess the possibility of optical communication with spacecraft by detecting pulses of light from powerful lasers which were to be directly imaged by *Galileo*'s CCD. The experiment, dubbed Galileo OPtical EXperiment or GOPEX, used two separate sites to beam laser pulses to the spacecraft, one at Table Mountain Observatory in California and the other at the Starfire Optical Range in New Mexico. The Table Mountain site used a frequency doubled Neodymium-Yttrium-Aluminium Garnet (Nd:YAG) laser operating at 532 nm with a repetition rate of ~15 to 30 Hz and a pulse power (FWHM) in the tens of megawatts range, which was coupled to a 0.6 meter Cassegrain telescope for transmission to *Galileo*; the Starfire range site used a similar setup with a larger transmitting telescope (1.5 m). Long exposure (~0.1 to 0.8 s) images using *Galileo'*s 560 nm centered green filter produced images of Earth clearly showing the laser pulses even at distances of up to 6,000,000 km. Adverse weather conditions, restrictions placed on laser transmissions by the U.S. Space Defense Operations Center (SPADOC) and a pointing error caused by the scan platform acceleration on the spacecraft being slower than expected (which prevented laser detection on all frames with less than 400 ms exposure times) all contributed to the reduction of the number of successful detections of the laser transmission to 48 of the total 159 frames taken. Nonetheless, the experiment was considered a resounding success and the data acquired will likely be used in the future to design laser "downlinks" which will send large volumes of data very quickly, from spacecraft to Earth. The scheme is already being studied (as of 2004) for a data link to a future Mars orbiting spacecraft.

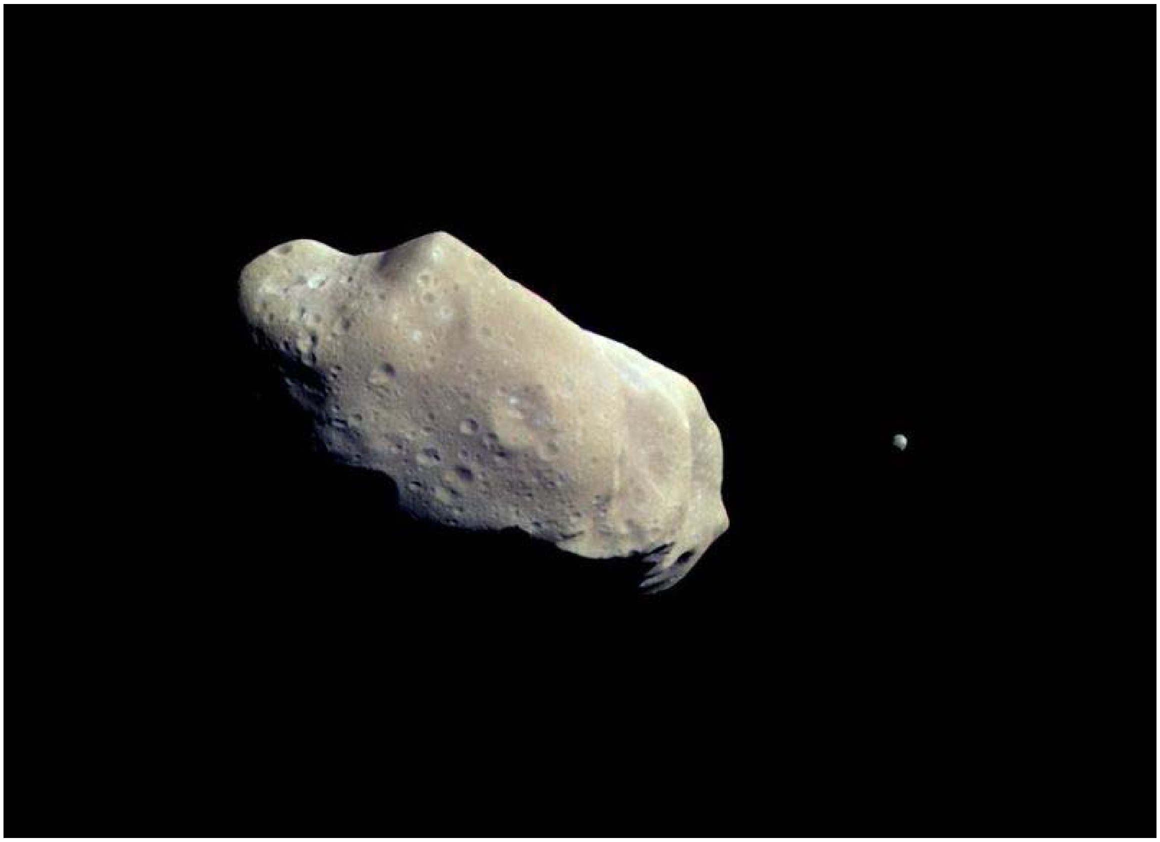
Asteroid encounters

NASA image of 951 Gaspra

First asteroid encounter: 951 Gaspra

On October 29, 1991, two months after entering the asteroid belt, *Galileo* performed the first ever asteroid encounter by passing about 1,600 kilometers (1,000 miles) from 951 Gaspra at a relative speed of about 8 kilometers per second (18,000 mph). Several pictures of Gaspra were taken along with measurements using the NIMS instrument to indicate composition and physical properties. The last (and best) two images were played back to Earth in November 1991 and June 1992. The imagery revealed a cratered and very irregular body about 19 by 12 by 11 kilometers (12 by 7.5 by 7 miles). The remainder of data taken, including low resolution images of more of the surface, were transmitted in late November 1992.

Second asteroid encounter: 243 Ida and Dactyl

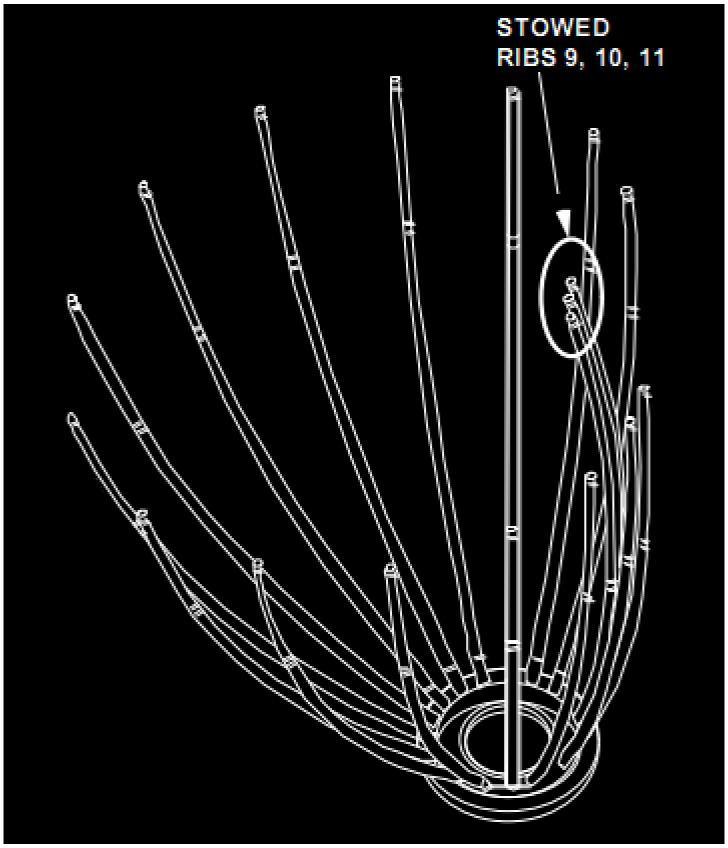


NASA image of 243 Ida. The tiny dot to the right is its moon, Dactyl.

Twenty-two months after the Gaspra encounter, on August 28, 1993, *Galileo* flew within 2,400 kilometers (1,500 miles) of asteroid 243 Ida. The probe discovered that Ida had a small moon, dubbed Dactyl, only 1.4 km in diameter which was the first asteroid moon discovered. Measurements using *Galileo*'s solid state imager, magnetometer and NIMS instrument were taken. From subsequent analysis of data, Dactyl appears to be an SII subtype S type asteroid and is spectrally different from 243 Ida. It is hypothesized that Dactyl may have been produced by partial melting within a Koronis parent body (Ida belongs to the "Koronis" family of asteroids that travels in the main Asteroid Belt between Mars and Jupiter) while the 243 Ida region escaped such igneous processing.

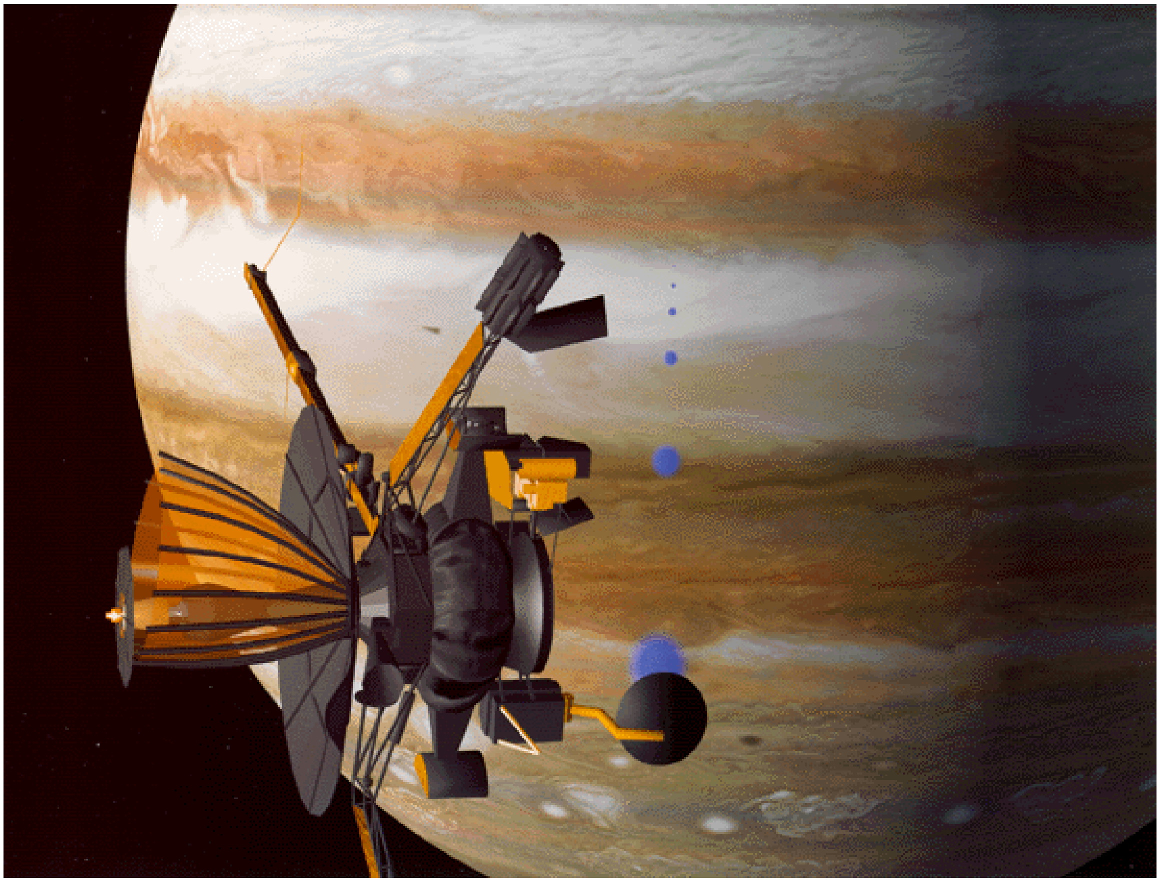
Spacecraft malfunctions

Main antenna failure



Laboratory tests verified that holding ribs 9, 10, and 11 in the stowed position most nearly modeled the spacecraft telemetry.

Artist's concept of *Galileo* at Io. Note the fully deployed high-gain antenna. Compare with below image.



Artist's concept of *Galileo* at Jupiter with only a partially deployed high-gain antenna

For reasons which are not currently known, and in all likelihood will never be known with certainty, *Galileo*'s high-gain antenna failed to fully deploy after its first flyby of Earth. Investigators speculate that during the time that *Galileo* spent in storage after the *Challenger* disaster, the lubricants evaporated, or the system was otherwise damaged. Engineers tried thermal cycling the antenna, rotating the spacecraft up to its maximum spin rate of 10.5 rpm, and "hammering" the antenna deployment motors - turning them on and off repeatedly - over 13,000 times; all attempts failed to open the high-gain antenna. Fortunately *Galileo* had an additional low-gain antenna that was capable of transmitting information back to Earth, though since it transmitted a signal isotropically, the low-gain antenna's bandwidth was significantly less than the high-gain antenna's would have been; the high-gain antenna was to have transmitted at 134 kilobits per second whereas the low-gain antenna was only intended to transmit at about 8 to 16 bits per second. *Galileo*'s low-gain antenna transmitted with a power of about 15 to 20 watts, which, by the time it reached Earth, and had been collected by one of the large aperture (70 m) DSN antennas, had a total power of about -170 dBm or 10 zeptowatts (10×10^{-21} watts). Through implementation of sophisticated data compression techniques, arraying of several Deep Space Network antennas and sensitivity upgrades of receivers used to listen to *Galileo*'s signal, data throughput was increased to a maximum of 160 bits per second. The data collected on Jupiter and its moons was stored in the on board tape recorder, and transmitted back to Earth during the long apozene portion of the probe's orbit using the low-gain antenna. At the same time, measurements were made of Jupiter's magnetosphere and transmitted back to Earth. The reduction in available bandwidth reduced the total amount of data transmitted throughout the mission to about 30 gigabytes and reduced the number of pictures that were transmitted significantly; in all, only around 14,000 images were returned.

Tape recorder anomalies and remote repair

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

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

Other radiation related anomalies

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

Near failure of atmospheric probe parachute

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

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

Galileo's end

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

Chapter- 2

NEAR Shoemaker

Artist's conception of the NEAR Shoemaker spacecraft

Flyby of	253 Mathilde
Satellite of	433 Eros
Orbital insertion date	2000-02-14 at 433 Eros
Orbits	230 orbits of 433 Eros
Launch date	20:43:27 UTC 1996-02-17
Launch vehicle	Booster: Delta 7925-8 Upper Stage: Star 48
Launch site	Cape Canaveral Air Force Station
Orbital decay	Never - landed on 433 Eros 2001-02-12

COSPAR ID	1996-008A
Homepage	http://near.jhuapl.edu/
Mass	Launch: ~800 kg On orbit dry: 487 kg
Power	Instruments: 81 w Total: 1800 w

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

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

Mission profile

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

Summary

Near-Earth asteroid Eros as seen from the NEAR spacecraft.

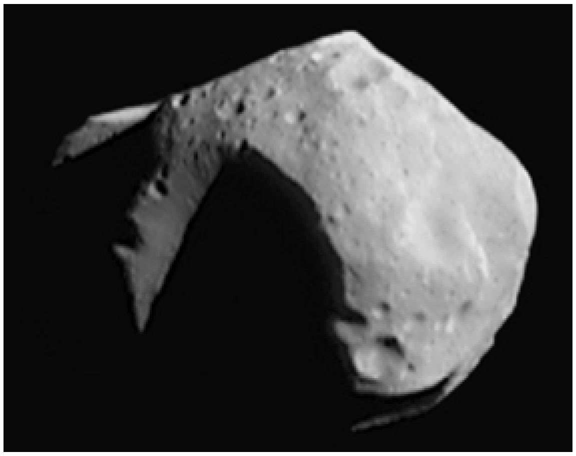
The primary goal of the mission was to study the near Earth asteroid 433 Eros from orbit for approximately one year. Eros is an S-type asteroid approximately 13 × 13 × 33 km in size, the second largest near-Earth asteroid. Initially the orbit was circular with a radius of 200 km. The radius of the orbit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

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

The journey to Eros

Launch of the NEAR spacecraft, February 1996.

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



One of the images from the flyby of 253 Mathilde.

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

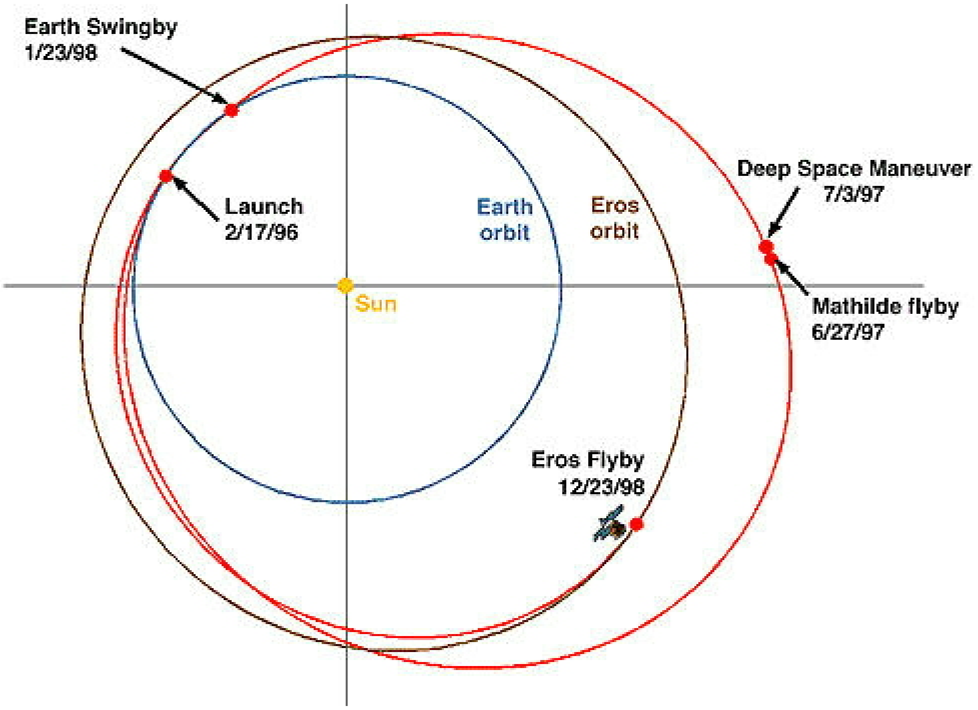
On July 3, 1997 NEAR executed the first major deep space maneuver, a two-part burn of the main 450 N thruster. This decreased the velocity by 279 m/s and lowered perihelion from 0.99 AU to 0.95 AU. The Earth gravity assist swingby occurred on January 23, 1998 at 7:23 UT. The closest approach was 540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

Failure of first attempt at orbital insertion

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

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

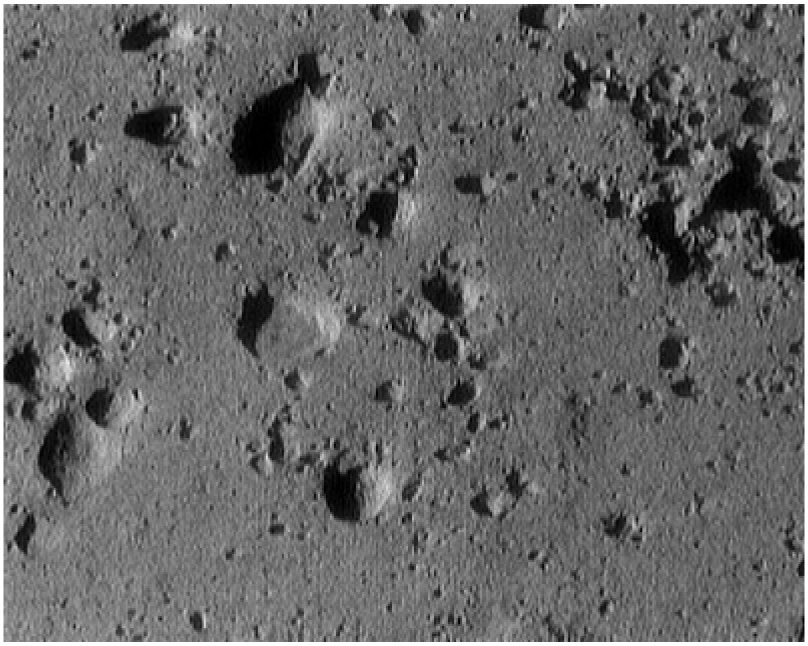
Orbital insertion



Trajectory graphic depicting the voyage of the NEAR spacecraft.

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

Orbits and landing

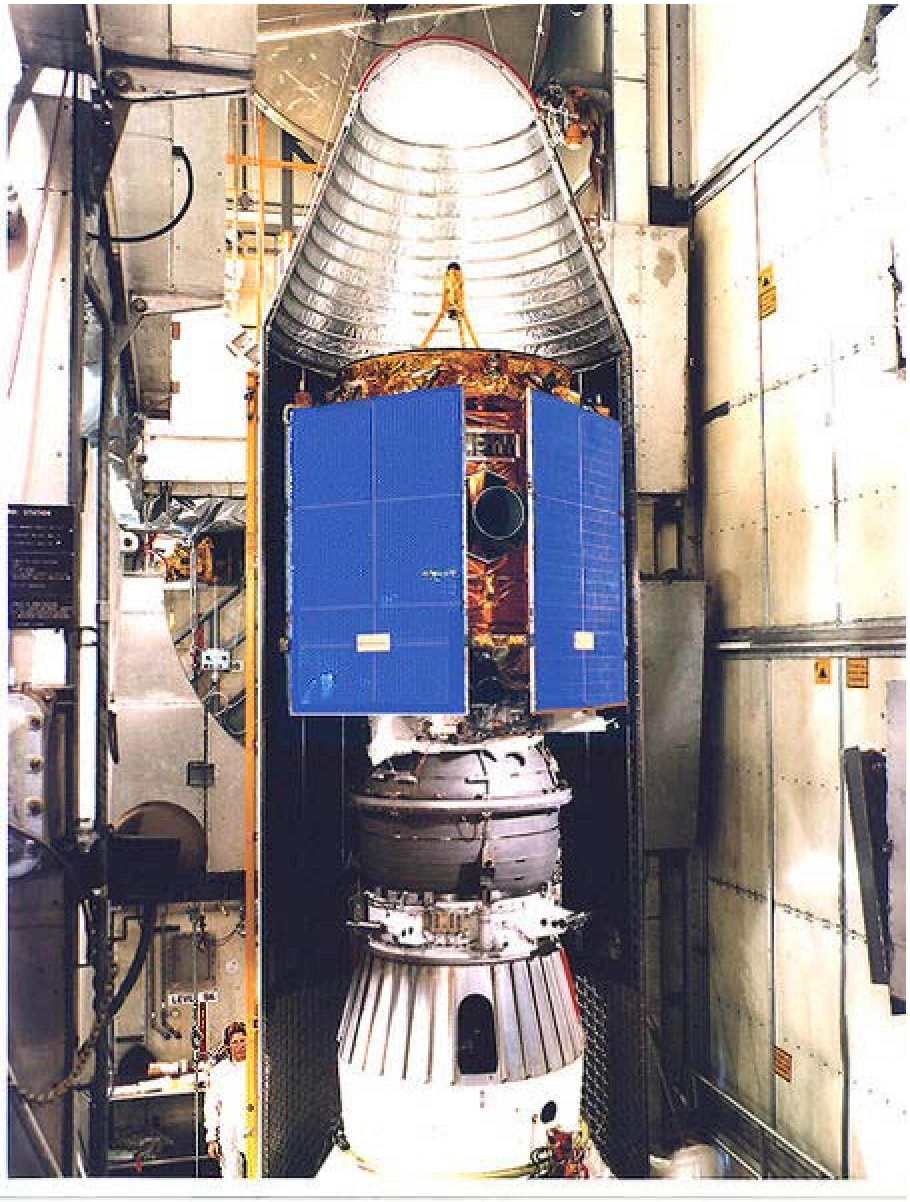


Eros asteroid from approximately 1,150 meters (area in image is roughly 54 meters wide). This image was taken during NEAR's descent to the surface of the asteroid.

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

At 7 p.m. EST on February 28, 2001 the last data signals were received from NEAR Shoemaker before it was shut down. A final attempt to communicate with the spacecraft on December 10, 2002 was unsuccessful. This was likely due to the extreme -279°F conditions the probe experienced while on Eros.

Spacecraft and subsystems



NEAR spacecraft inside its Delta II rocket.

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

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

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

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

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

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

Chapter- 3

Deep Space 1

Deep Space 1

Artist rendering of *Deep Space I*'s flyby of comet 19P/Borrelly

Operator	NASA / JPL
Major contractors	Spectrum Astro
Mission type	Flyby
Flyby of	Braille, Borrelly
Launch date	1998-10-24 12:08:00 UTC (12 years, 3 months, and 29 days ago)
Launch vehicle	Delta II 7326
Launch site	Space Launch Complex 17A Cape Canaveral Air Force Station
Mission	July 29, 1999 - December 18, 2001

duration	Braille flyby *(completed 1999-07-29)* Borrelly flyby *(completed 2001-09-22)*
COSPAR ID	1998-061A
Homepage	Deep Space 1
Mass	373 kg (822 lb)
Power	2500 W (Solar Concentrator Array/batteries)
	Orbital elements
Eccentricity	0.143
Inclination	0.4°
Apoapsis	1.32 AU
Periapsis	0.99 AU
Orbital period	453 days
	Instruments
Main instruments	Miniature Integrated Camera Spectrometer (MICAS) Plasma Experiment for Planetary Exploration (PEPE) The Ion Propulsion System (IPS) Diagnostic Subsystem (IDS)

Deep Space 1 (DS1) of the NASA New Millennium Program is a spacecraft dedicated to testing its payload of advanced, high risk technologies. Launched on 24 October 1998, three of twelve technologies on board had to work within a few minutes of separation from the carrier rocket for the mission to continue. The Deep Space mission carried out a flyby of asteroid 9969 Braille which was selected as the mission's science target. Its mission was extended twice to include an encounter with Comet Borrelly and further engineering testing. Problems during its initial stages and with its star tracker led to repeated changes in mission configuration. While the flyby of the asteroid was a partial success, the encounter with the comet retrieved valuable information.

The Deep Space series was continued by the Deep Space 2 probes, which were launched in January 1999 on Mars Polar Lander and were intended to strike the surface of Mars.

Technologies

Autonav

The Autonav system, developed by NASA's Jet Propulsion Laboratory, takes images of known bright asteroids. The asteroids in the inner Solar System move in relation to other bodies at a noticeable, predictable speed. Thus a spacecraft can determine its relative position by tracking such asteroids across the star background, which appears fixed over such timescales. Two or more asteroids let the spacecraft triangulate its position; two or more positions in time let the spacecraft determine its trajectory. Existing spacecraft are tracked by their interactions with the transmitters of the Deep Space Network (DSN), in effect an inverse GPS. However, DSN tracking requires many skilled operators, and the DSN is overburdened by its use as a communications network. The use of Autonav reduces mission cost and DSN demands.

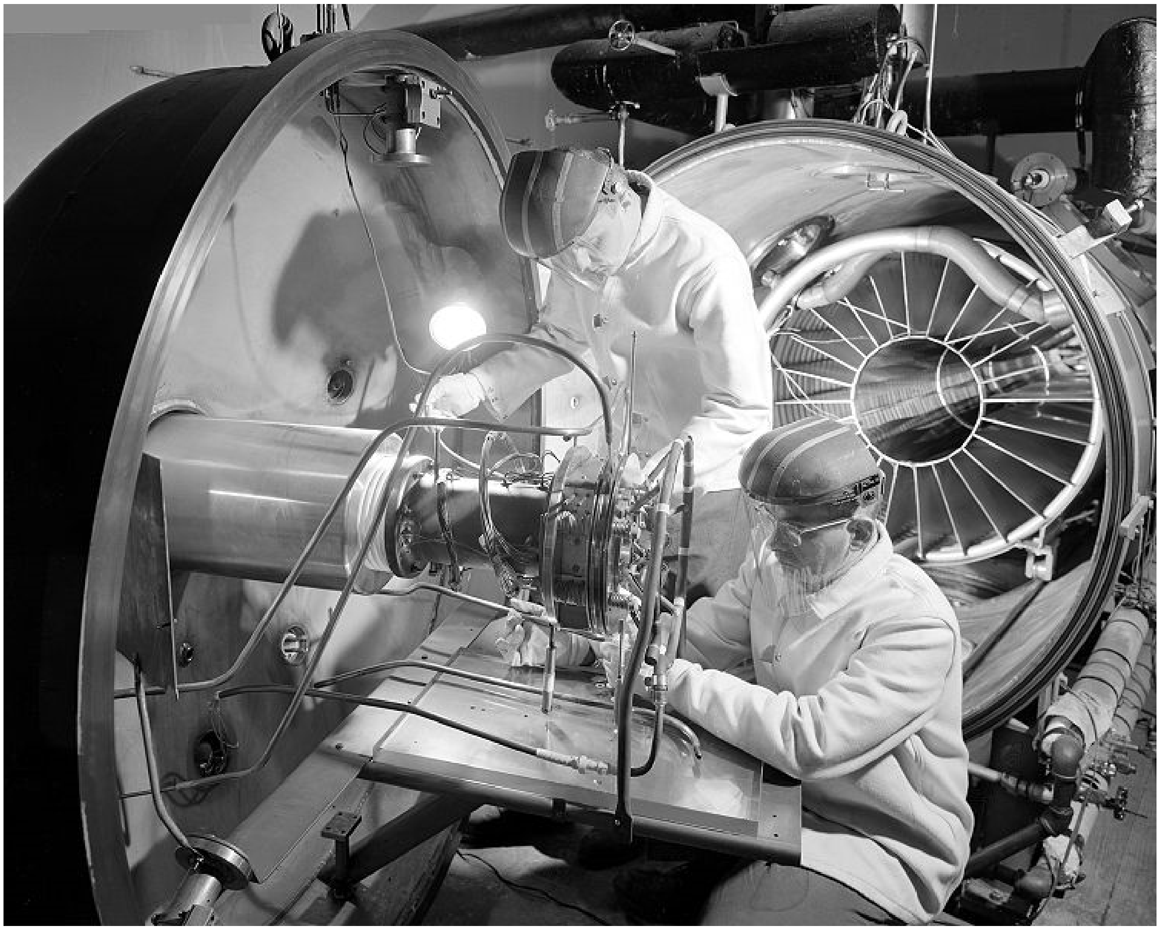
The Autonav system can also be used in reverse, tracking the position of bodies relative to the spacecraft. This is used to acquire targets for the scientific instruments. The spacecraft is programmed with the target's coarse location. After initial acquisition, Autonav keeps the subject in frame, even commandeering the spacecraft's attitude control. The next spacecraft to use Autonav was Deep Impact.

SCARLET concentrating solar array

Primary power for the mission was produced by a new solar array technology, the Solar Concentrator Array of Refractive Linear Element Technologies ("SCARLET") solar arrays, developed at NASA's Glenn Research Center. These use linear Fresnel lenses made of silicone to concentrate sunlight onto solar cells. The concentrating array technology was combined with dual-junction solar cells, which had considerably better performance than the GaAs solar cells that were the state of the art at the time of the mission launch.

The SCARLET arrays generate 2.5 kilowatts at 1 AU, with less size and weight than conventional arrays.

NSTAR ion engine



Technicians are installing ion engine #1 in the High Vacuum Tank in the Electric Propulsion Research Building in this image from 1959.

The fully assembled Deep Space 1 probe

The Deep Space 1 experimental solar-powered ion propulsion engine

Past, Present, Future

Although ion engines had been developed at NASA since the late 1950s, with the exception of the SERT missions in the 1960s, the technology had not been demonstrated in flight. This lack of a performance history in space meant that despite the potential savings in propellant mass, the technology was considered too experimental to be being used for high-cost missions. It was a primary mission of the Deep Space 1 demonstration to show long duration use of an ion thruster on a science mission. Deep Space 1 was the first use of ion engines on an operational science spacecraft.

The NSTAR electrostatic ion thruster, developed at NASA Glenn, achieves a specific impulse of one to three thousand seconds. This is an order of magnitude higher than traditional space propulsion methods, resulting in a mass savings of approximately half.

This leads to much cheaper launch vehicles. Although the engine produces just 92 millinewtons (0.331 ounce-force) thrust at maximum power, the craft achieved high speeds because ion engines thrust continuously for long periods. The engine fired for 678 total days, a record for such engines. The next spacecraft to use NSTAR engines was the Dawn Mission, with three redundant units.

Remote Agent

Remote Agent (remote intelligent self-repair software)(RAX), developed at NASA Ames Research Center and JPL, was the first artificial intelligence control system to control a spacecraft without human supervision. Remote Agent successfully demonstrated the ability to plan onboard activities and correctly diagnose and respond to simulated faults in spacecraft components. Autonomous control will enable future spacecraft to operate at greater distances from Earth, and to carry out more sophisticated science-gathering activities in deep space. Components of the Remote Agent software have been used to support other NASA Missions. Major components of Remote Agent were a robust planner (EUROPA), a plan execution system (EXEC) and a model-based diagnostic system (Livingstone). EUROPA was used as a ground-based planner for the Mars Exploration Rovers. EUROPA II was used to support the Phoenix Mars Lander and will support the upcoming Mars Science Laboratory. Livingstone2 was flown as an experiment onboard Earth Observing 1, and an F-18 at NASA Dryden Flight Research Center.

Beacon Monitor

Another method for reducing DSN burdens is the Beacon Monitor experiment. During the long cruise periods of the mission, spacecraft operations are essentially suspended. Instead of data, the craft emits a carrier signal on a predetermined frequency. Without data decoding, the carrier can be detected by much simpler ground antennas and receivers. If the spacecraft detects an anomaly, it changes the carrier between four tones, based on urgency. Ground receivers then signal operators to divert DSN resources. This prevents skilled operators and expensive hardware from babysitting an unburdened mission operating nominally. A similar system is used on the New Horizons Pluto probe to keep costs down during its ten-year cruise from Jupiter to Pluto.

SDST

The Small Deep Space Transponder (SDST) is a compact and light weight radio communications system. Aside from using miniaturized components, the SDST is capable of communicating over the K_a band. Because this band is higher in frequency than bands currently in use by deep-space missions, the same amount of data can be sent by smaller equipment in space and on the ground. Conversely, existing DSN antennas can split time among more missions. At the time of launch, the DSN had a small number of K_a receivers installed on an experimental basis; K_a operations and missions are increasing.

PEPE

Once at a target, DS1 senses the particle environment with the PEPE (Plasma Experiment for Planetary Exploration) instrument. It maps the objects with the MICAS (Miniature Integrated Camera And Spectrometer) imaging channel, and discerns chemical composition with infrared and ultraviolet channels. All channels share a 10 cm telescope, which uses a silicon carbide mirror.

Achievements

Comet 19P/Borrelly imaged just 160 seconds before Deep Space 1's closest approach.

The ion propulsion engine initially failed after 4.5 minutes of operation. However, it was later restored to action and performed excellently. Early in the mission, material ejected during launch vehicle separation caused the closely-spaced ion extraction grids to short-circuit. The contamination was eventually cleared, as the material was eroded by electrical arcing, sublimed by outgassing, or simply allowed to drift out. This was achieved by repeatedly restarting the engine in an engine repair mode, arcing across trapped material.

It was thought that the ion exhaust might interfere with other spacecraft systems, such as radio communications or the science instruments. The PEPE detectors had a secondary function to monitor such effects from the engine. No interference was found.

Another failure was the loss of the star tracker. The star tracker determines spacecraft orientation by comparing the star field to its internal charts. The mission was saved when the MICAS camera was reprogrammed to substitute for the star tracker. Although MICAS is more sensitive, its field-of-view is an order of magnitude smaller, creating a greater information processing burden. Ironically, the star tracker was an off-the-shelf component, expected to be highly reliable.

Without a working star tracker, ion thrusting was temporarily suspended. The loss of thrust time forced the cancellation of a flyby past Comet Wilson-Harrington.

The Autonav system required occasional manual corrections. Most problems were in identifying objects that were too dim, or were difficult to identify because of brighter objects causing diffraction spikes and reflections in the camera, causing Autonav to misidentify targets.

The Remote Agent system was presented with three simulated failures on the spacecraft and correctly handled each event.

1. a failed electronics unit, which Remote Agent fixed by reactivating the unit.
2. a failed sensor providing false information, which Remote Agent recognized as unreliable and therefore correctly ignored.
3. an attitude control thruster (a small engine for controlling the spacecraft's orientation) stuck in the "off" position, which Remote Agent detected and compensated for by switching to a mode that did not rely on that thruster.

Overall this constituted a successful demonstration of fully autonomous planning, diagnosis, and recovery.

The MICAS instrument was a design success, but the ultraviolet channel failed due to an electrical fault. Because MICAS was reprogrammed for use as a star tracker, no usable scientific data was returned.

The flyby of the asteroid 9969 Braille was only a partial success. Deep Space 1 was intended to perform the flyby at 56,000 km/h (34,797 mph) at only 240 m (787 ft) from the asteroid. Due to technical difficulties, including a software crash shortly before approach, the craft instead passed Braille at a distance of 26 km (16 mi). This, plus Braille's lower albedo, meant that the asteroid was not bright enough for the autonav to focus the camera in the right direction, and the picture shoot was delayed by almost an hour. The resulting pictures were disappointingly indistinct.

However, the flyby of Comet Borrelly was a great success and returned extremely detailed images of the comet's surface. Such images were of higher resolution than the only previous pictures, of Halley's Comet taken by the Giotto spacecraft. The PEPE instrument reported that the comet's fields were offset from the nucleus. This is believed to be due to emission of jets, which were not distributed evenly across the comet's surface.

Despite having no debris shields, the spacecraft survived the comet passage intact. Once again, the sparse comet jets did not appear to point towards the spacecraft. The spacecraft eventually ran out of hydrazine fuel for its attitude control thrusters. The highly efficient ion thruster had a sufficient amount of propellant left to perform attitude control in addition to main propulsion, thus allowing the mission to continue.

Current status

Launch of Deep Space 1 from Cape Canaveral Air Force Station Space Launch Complex 17-A on the Delta II 7326-9.5 Star 37FM

Deep Space 1 succeeded in its primary and secondary objectives including flybys of the asteroid Braille and of Comet Borrelly, returning valuable science data and images. DS1's ion engines were shut down on 18 December 2001 at approximately 20:00:00 UTC, signaling the end of the mission. However, on-board communications remain active in case the craft is needed in the future.

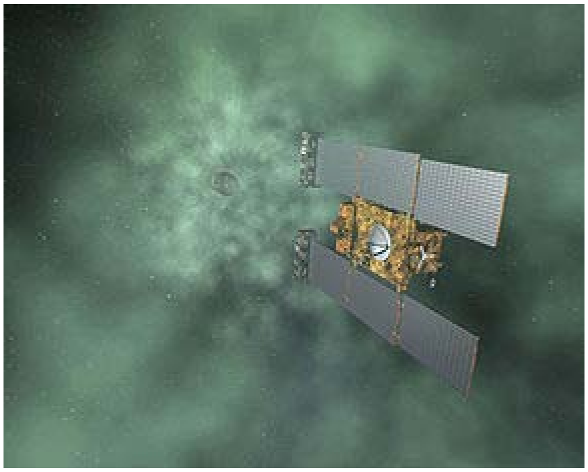
Statistics

- the mass of the craft: 486.3 kg (1072 lb 2 oz) (with fuel)
- total cost: US$149.7 million
- development cost: US$94.8 million
- prime contractor: Spectrum Astro, later acquired by General Dynamics
- launch site: Cape Canaveral Air Station, Florida
- launch vehicle: Boeing Delta II model 7326
- maximum power: 2,500 W (of which 2,100 W powers the ion thrust engine)
- project manager: Dr. Marc Rayman

Chapter- 4

Stardust (Spacecraft)

Stardust



Artist rendering of *Stardust-NExT* on approach to comet Tempel 1

Operator	NASA / JPL
Major contractors	Lockheed Martin
Mission type	Flyby, Sample return
Flyby of	5535 Annefrank, Wild 2, Tempel 1
Satellite of	Sun
Launch date	1999-02-07 21:04:15 UTC (12 years and 16 days ago)
Launch vehicle	Delta II 7426
Launch site	Space Launch Complex 17A

	Cape Canaveral Air Force Station
Mission duration	In progress (NeXT) (8 years, 3 months, and 21 days elapsed) Annefrank flyby *(completed 2002-11-02)* Wild 2 flyby *(completed 2004-01-02)* Sample return *(completed 2006-01-15)* Primary mission *(completed 2006-01-15)* Tempel 1 flyby *(completed 2011-02-14)*
Landing site	40°21.9′N 113°31.25′W / 40.365°N 113.52083°W Utah Test and Training Range
COSPAR ID	1999-003A
Homepage	Stardust homepage NExT homepage
Mass	300 kg (661 lb)
Power	330 W (Solar array / NiH_2 batteries)

Stardust is a 300-kilogram robotic space probe launched by NASA on February 7, 1999 to study the asteroid 5535 Annefrank and collect samples from the coma of comet Wild 2. The primary mission was completed January 15, 2006, when the sample return capsule returned to Earth. Operating for 12 years and 16 days, *Stardust* intercepted comet Tempel 1 on February 15, 2011, a small Solar System body previously visited by *Deep Impact* on July 4, 2005. It is the first sample return mission to collect cosmic dust and return the sample to Earth and the first to acquire images of a previously visited comet.

Mission background

History

Beginning in the 1980s, scientists began seeking a dedicated mission to study a comet. During the early 1990s, several missions to study comet Halley became the first successful missions to return close-up data. However, the US cometary mission, Comet Rendezvous Asteroid Flyby, was canceled for budgetary reasons. In the mid-1990s, further support was given to a cheaper, Discovery-class mission that would study comet Wild 2 in 2004.

Stardust was competitively selected in the fall of 1995 as a NASA Discovery Program mission of low-cost with highly focused science goals [:5]. Construction of Stardust began in 1996, and was subject to the maximum contamination restriction, level 5 planetary protection. However, the risk of interplanetary contamination by alien life was judged low, as particle impacts at over 1000 miles per hour, even into aerogel, were believed to be terminal for any known microorganism. [:22-23]

Comet Wild 2 was selected as the primary target of the mission for the rare chance to observe a long-period comet that has ventured close to the Sun. The comet has since become a short period comet after an event in 1974, where the orbit of Wild 2 was affected by the gravitational pull of Jupiter, moving the orbit inward, closer to the Sun. In planning the mission, it was expected that most of the original material from which the comet formed, would still be preserved. [:5]

The primary science objectives of the mission include:

- Provide a flyby of a comet of interest (Wild 2) at a sufficiently low velocity (less than 6.5 km/s) such that non-destructive capture of comet dust is possible using an aerogel collector.
- Facilitate the intercept of significant numbers of interstellar dust particles using the same collection medium, also at as low a velocity as possible.
- Return as many high resolution images of the comet coma and nucleus as possible, subject to the cost constraints of the mission.

The spacecraft was designed, built and is operated by Lockheed Martin Astronautics as a Discovery-class mission in Denver, Colorado. JPL provides mission management for the NASA division for mission operations. The principal investigator of the mission is Dr. Donald Brownlee from the University of Washington. [:5]

Stardust Microchip

Stardust was launched carrying two sets of identical pairs of square 10.16-centimeter silicon wafers. Each pair features engravings of well over one-million names of people who participated in the public outreach program by filling out internet forms available in late 1997 and mid 1998. One pair of the microchips is positioned on the spacecraft and the other was attached to the sample return capsule. [:24]

Spacecraft design

The spacecraft bus measures 1.7-meters in length, and 0.66-meters in width, a design adapted from the SpaceProbe deep space bus developed by Lockheed Martin Astronautics. The bus is primarily constructed with graphite fiber panels with an aluminum honeycomb support structure underneath; the entire spacecraft is covered with polycyanate, Kapton sheeting for further protection. To maintain low costs, the spacecraft incorporates many designs and technologies used in past missions or previously developed for future missions by the Small Spacecraft Technologies Initiative (SSTI). The spacecraft features five scientific instruments to collect data, including the Stardust Sample Collection tray, which was brought back to Earth for analysis.

Attitude control and propulsion

The spacecraft is three-axis stabilized with eight 4.41-N hydrazine monopropellant thrusters, and eight 1-N thrusters to maintain attitude control; necessary minor propulsion maneuvers are performed by these thrusters as well. The spacecraft was launched with 80-kilograms of propellant. Information for spacecraft positioning is provided by a star tracker, an inertial measurement unit, and two sun sensors. [:30-31]

Communications

For communicating with the Deep Space Network, the spacecraft transmits data across the x-band using a 0.6-meter parabolic high-gain antenna and a 15-watt transponder design originally intended for the Cassini spacecraft. [:32]

Power

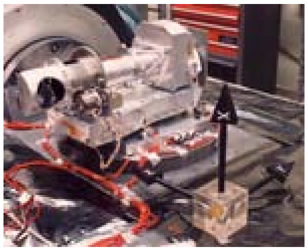
The probe is powered by two solar arrays, providing an average of 330-watts of power. The arrays also include whipple shields to protect the delicate surfaces from the potentially damaging cometary dust while the spacecraft is in the coma of Wild 2. The solar array design is derived primarily from the Small Spacecraft Technology Initiative (SSTI) spacecraft development guidelines. A single nickel hydrogen (NiH_2) battery is also included to provide the spacecraft with power when the solar arrays receive too little sunlight. [:31]

Computer

The computer on the spacecraft operates using a radiation hardened RAD6000 32-bit processor card. For storing data when the spacecraft is unable to communicate with Earth, the processor card is able to store 128-megabytes, 20% of which is occupied by the flight system software. The system software is a form of VxWorks, an embedded operating system developed by Wind River Systems.[:31]

Scientific instruments

Navigation Camera (**NC**)



The camera is intended for targeting comet Wild 2 during the flyby of the nucleus. It captures black and white images through a filter wheel making it possible to assemble color images and detect certain gas and dust emissions in the coma. It also captures images at various phase angles, making it possible to create a three dimensional model of a target to better understand the origin, morphology, and mineralogical inhomogeneities on the surface of the nucleus. The camera utilizes the optical assembly from the Voyager Wide Angle Camera. It is additionally fitted with a scanning mirror to vary the viewing angle and avoid potentially damaging particles.

Objectives

- **Lead investigator:** Ray Newburn / JPL
- **Data:** PDS/SBN data catalog

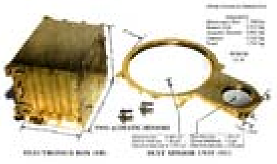
Cometary and Interstellar Dust Analyzer (**CIDA**)

The dust analyzer is a mass spectrometer able to provide real-time detection and analysis of certain compounds and elements. Particles enter the instrument after colliding with a silver impact plate and traveling down a tube to the detector. The detector is then able to detect the mass of separate ions by measuring the time taken for each ion to enter and travel through the instrument. Identical instruments were also included on Giotto and Vega 1 and 2.

Objectives

- **Lead investigator:** Jochen Kissel / Max-Planck-Institut fur Aeronomie (webstite -archived)
- **Data:** PDS/SBN data archives: Early calib, Annefrank, Raw Wild 2, Calib Wild 2

Dust Flux Monitor Instrument (**DFMI**)



Located on the whipple shield at the front of the spacecraft, the sensor unit provides data regarding the flux and size distribution of particles in the environment around Wild 2. It records data by generating electric pulses as a special polarized plastic (PVDF) sensor is struck by high energy particles as small as a few micrometers.

Objectives

- **Lead investigator:** Anthony Tuzzolino / University of Chicago (website)
- **Data:** PDS/SBN data archive, PDS/SBN EDR data archive

Stardust Sample Collection (**SSC**)

The particle collector uses aerogel, a low-density, inert, microporous, silica-based substance, to capture dust grains as the spacecraft passes through the coma of Wild 2. After sample collection was complete, the collector receded into the Sample Return Capsule for entering the Earth's atmosphere. The capsule with encased samples would be retrieved from Earth's surface and studied.

Objectives

- **Principal investigator:** Donald Brownlee / University of Washington
- **Data:** PDS/SBN temperature data archive, PDS/SBN positioning data archive

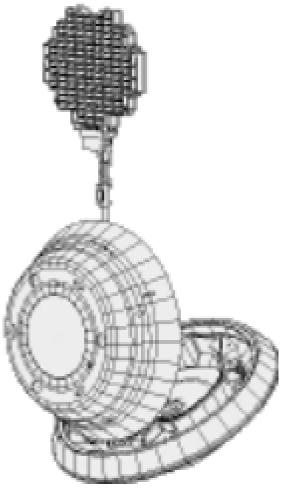
Dynamic Science Experiment (**DSE**)

The experiment will primarily utilize the X band telecommunications system to conduct radio science on Wild 2, to determine the mass of the comet; secondarily the inertial measurement unit is utilized to estimate the impact of large particle collisions on the spacecraft.

Objectives

- **Lead investigator:** John Anderson / JPL
- **Data:** PDS/SBN data archive

Sample collection



Stardust capsule with aerogel collector deployed

Comet and interstellar particles are collected in ultra low density aerogel. The tennis racket-sized collector tray contains ninety blocks of aerogel, providing more than 1,000 square centimeters of surface area to capture cometary and interstellar dust grains.

To collect the particles without damaging them, a silicon-based solid with a porous, sponge-like structure is used in which 99.8 percent of the volume is empty space. Aerogel is 1,000 times less dense than glass, another silicon-based solid. When a particle hits the aerogel, it becomes buried in the material, creating a long track, up to 200 times the length of the grain. The aerogel was packed in an aluminum grid and fitted into a Sample Return Capsule (SRC), which was to be released from the spacecraft as it passed Earth in 2006.

To analyze the aerogel for interstellar dust, one million photographs will be needed to image the entirety of the sampled grains. The images will be distributed to home computer users to aid in the study of the data using a program titled, Stardust@home.

Images of the spacecraft

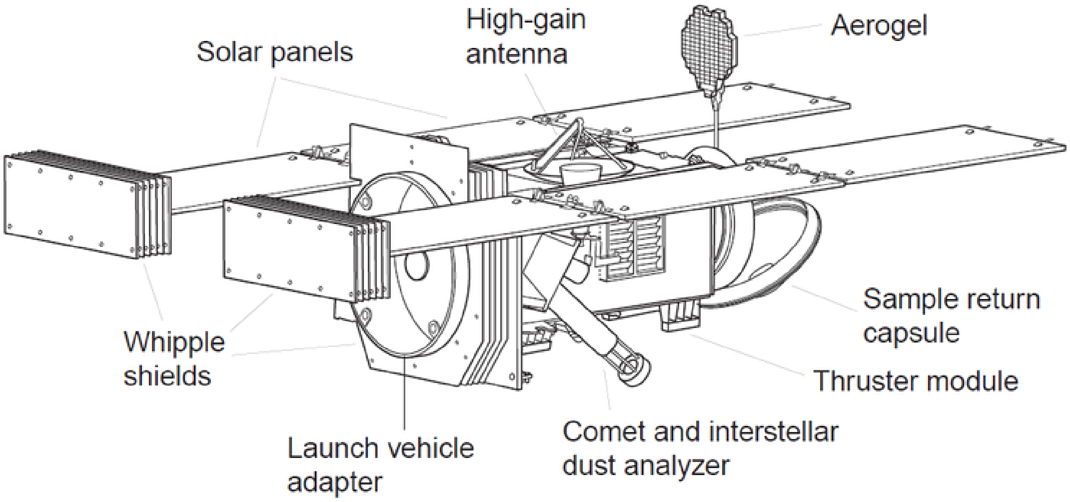


Diagram of the spacecraft.

Stardust awaiting testing of the solar arrays.

The solar arrays being checked in the Payload Hazardous Servicing Facility.

Stardust being checked before encapsulation.

Mission profile

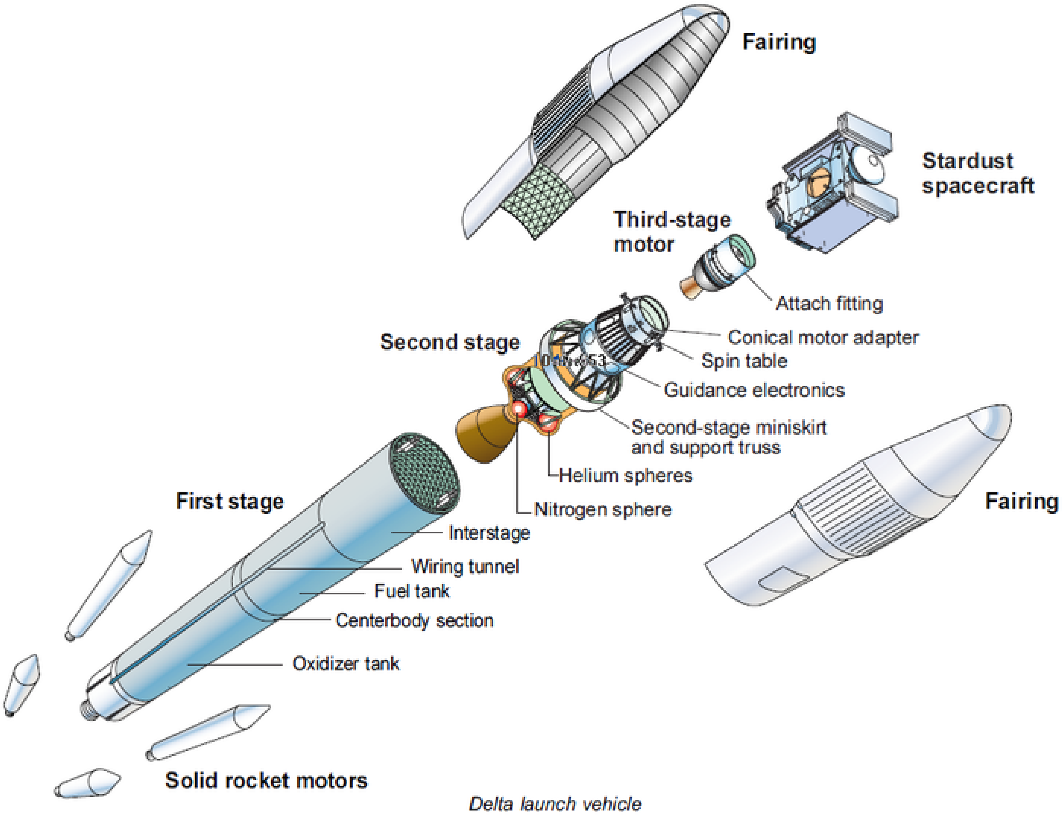
Launch and trajectory

Stardust was launched on February 7, 1999, at 21:04:15 UTC by the National Aeronautics and Space Administration from Space Launch Complex 17A at the Cape Canaveral Air Force Station in Florida, aboard a Delta II 7426 launch vehicle. The complete burn sequence lasted for 27 minutes bringing the spacecraft into a heliocentric orbit that would bring the spacecraft around the Sun and past Earth for a gravity assist maneuver in 2001, to reach asteroid Annefrank in 2002 and comet Wild 2 in 2004 at a low flyby velocity of 6.1 km/s. In 2004, the direction of the spacecraft performed a deep space maneuver that would allow it to pass by Earth a second time in 2006, to release the Sample Return Capsule for a landing in Utah. [:14-22]

During the second encounter with Earth, Stardust was put into a "divert maneuver" immediately after the capsule was released. The maneuver corrected the spacecraft direction to avoid entering the atmosphere. Under twenty kilograms of propellant remained onboard after the maneuver.

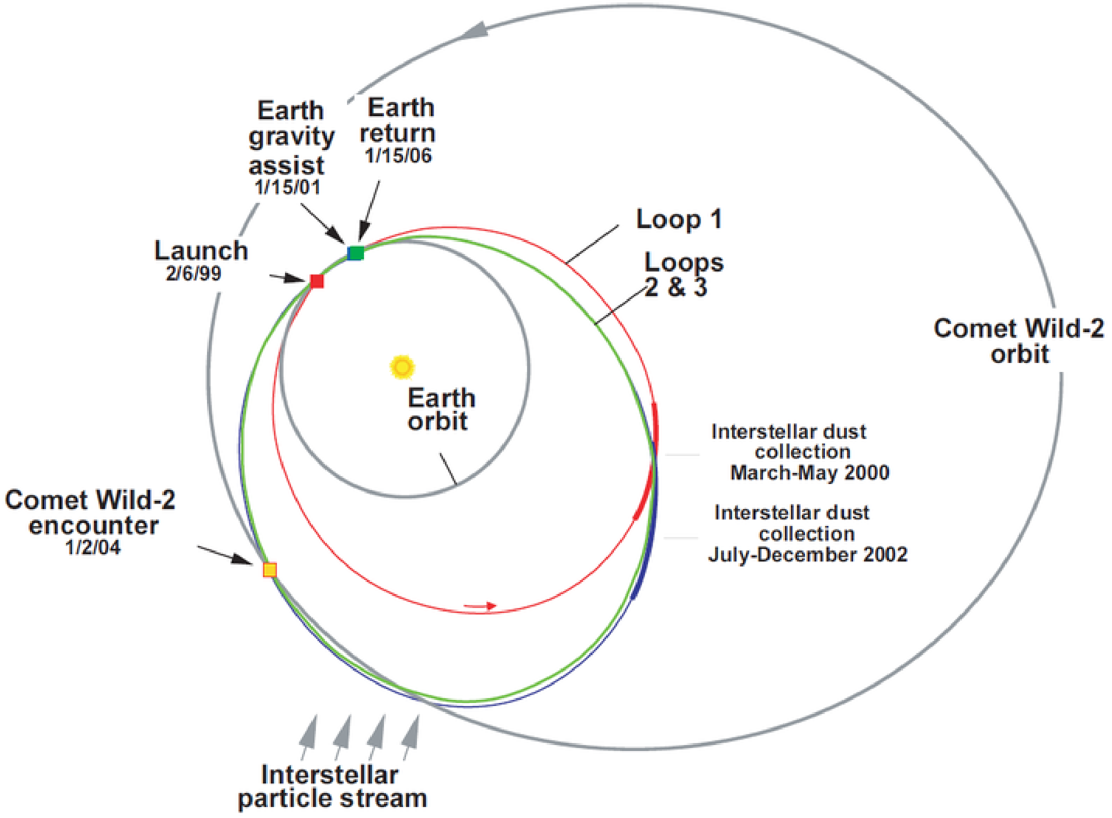
On January 29, 2004, the spacecraft was put in hibernation mode with only the solar panels and receiver active, in a three-year heliocentric orbit that would return it to Earth vicinity on January 14, 2009.

A subsequent mission extension was approved on July 3, 2007, to bring the spacecraft back to full operation for a flyby of comet Tempel 1 in 2011. The mission extension will be the first to revisit a small solar system body and is expected to use the remaining propellant, signaling the end of the useful life for the spacecraft.



Exploded diagram of the Delta II vehicle with Stardust.

Photo of Stardust during launch with a Delta II launch vehicle.



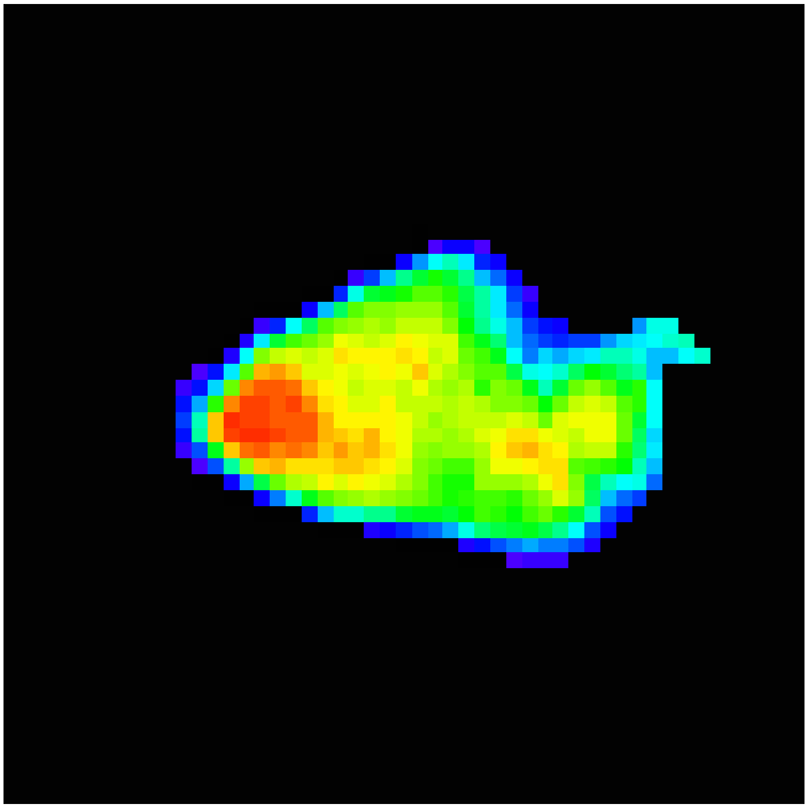
Mission trajectory

Trajectory of the Stardust spacecraft en route to Wild 2.

Encounter with Annefrank

On November 2, 2002, at 04:50:20 UTC, Stardust encountered asteroid 5535 Annefrank from a distance of 3,079 km (1,913 mi). The solar phase angle ranged from 130 deg to 47 degrees during the period of observations. This encounter was used primarily as an engineering test of the spacecraft and ground operations in preparation for the encounter with comet Wild 2 in 2003.

Image of asteroid Annefrank captured on November 2, 2002.



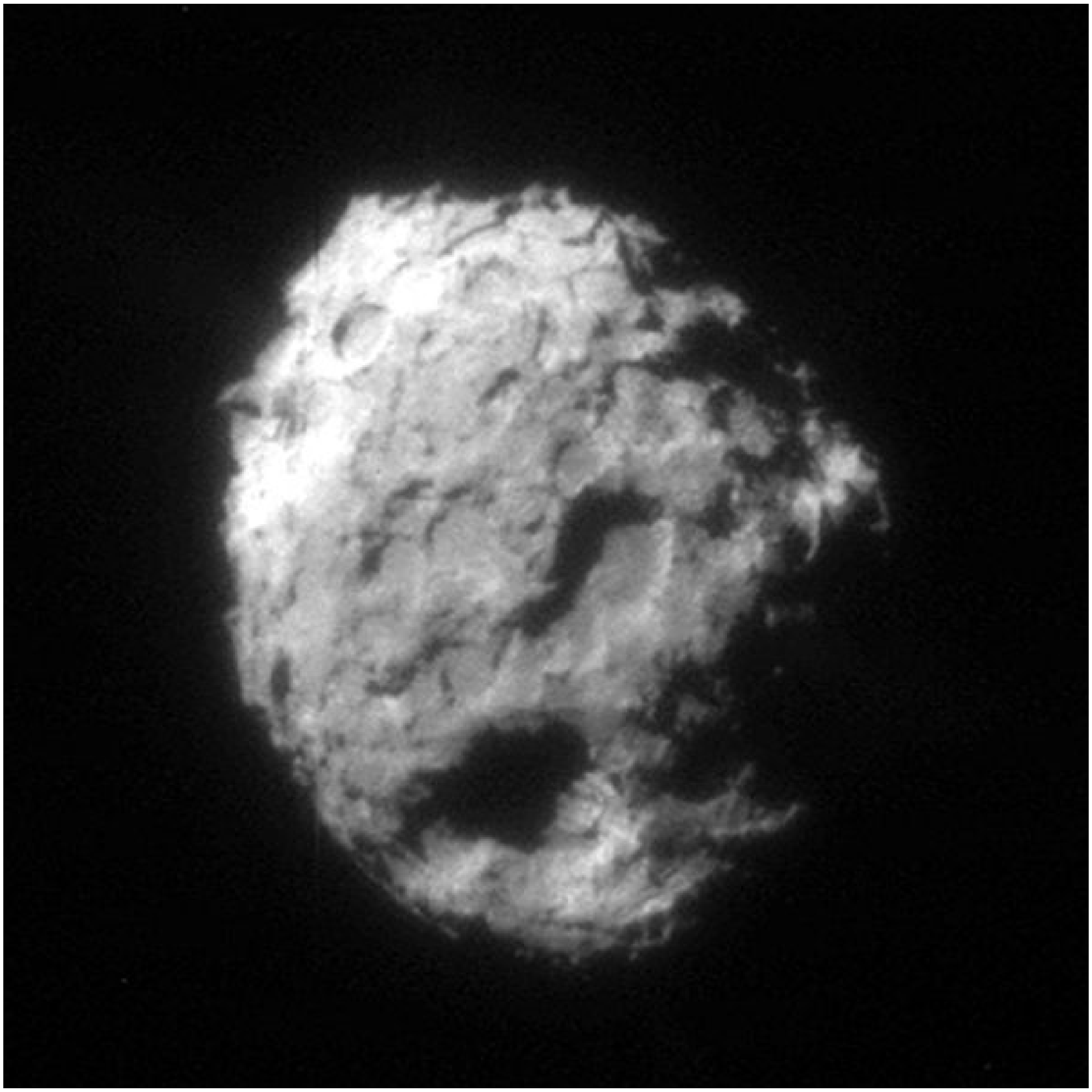
False-color image of asteroid Annefrank showing the irregular shape of the object.

Encounter with Wild 2

On January 2, 2004, at 19:21:28 UTC, Stardust encountered Comet Wild 2 on the sunward side with a relative velocity of 6.1 km/sec at a distance of 237 km (147 mi). The original encounter distance was planned to be 150 km (93 mi), but this was changed after a safety review board increased the closest approach distance to minimize the potential for catastrophic dust collisions.

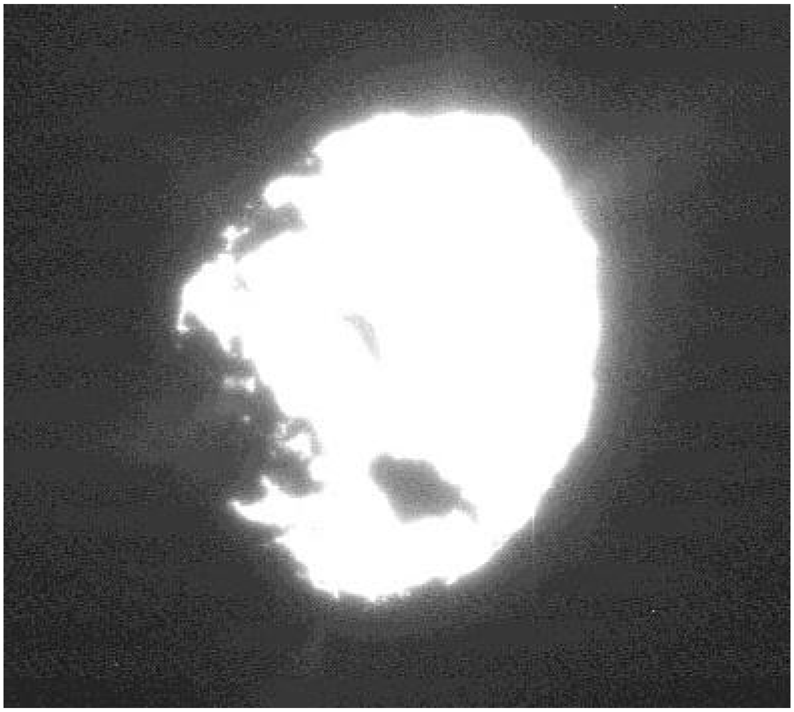
The relative velocity between the comet and the spacecraft was such that the comet actually overtook the spacecraft from behind as they traveled around the Sun. During the encounter, the spacecraft was on the sun-lit side of the nucleus, approaching at a solar phase angle of 70 degrees, reaching a minimum angle of 3 degrees near closest approach and departing at a phase angle of 110 degrees.

During the flyby the spacecraft deployed the Sample Collection plate to collect dust grain samples from the coma, and took detailed pictures of the icy nucleus.

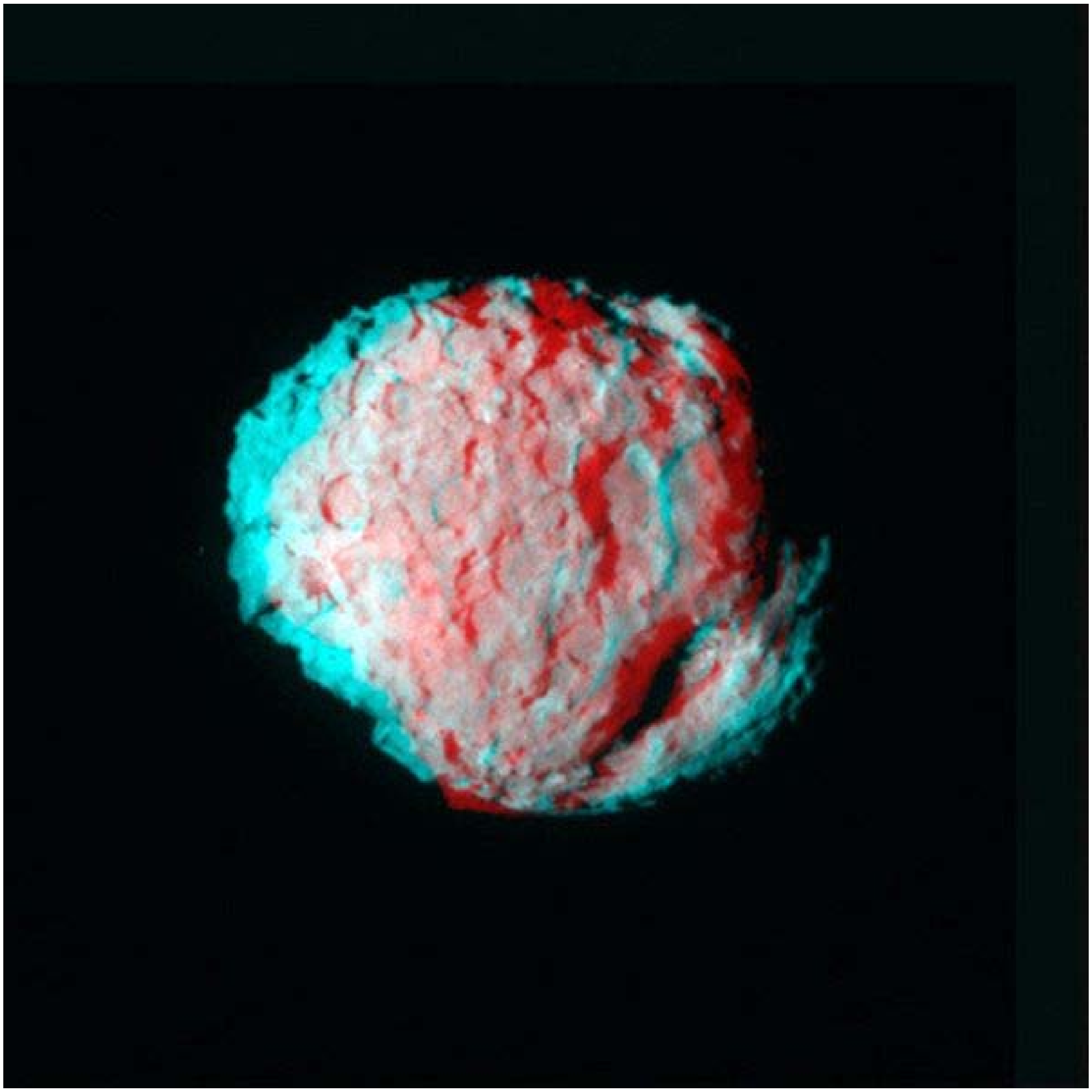


Comet Wild 2 as seen from Stardust on January 2, 2004.

Image of Wild 2 taken during the closest approach phase.



An overexposed image of Wild 2 showing plumes of material.



A 3D anaglyph of comet Wild 2

Sample return

Landing capsule as seen by the recovery team.

On January 16, 2006, at 05:57:00 UTC, the Sample Return Capsule successfully separated from Stardust and re-entered the Earth's atmosphere at 09:57:00 UTC, at a velocity of 12.9 km/s, the fastest re-entry speed into Earth's atmosphere ever achieved by a man-made object. The capsule then parachuted to the ground, finally landing at 10:10:00 UTC at the Utah Test and Training Range (40°21.9′N 113°31.25′W / 40.365°N 113.52083°W), near the U.S. Army Dugway Proving Ground. The capsule was then transported by military aircraft from Utah to Ellington Air Force Base in Houston, Texas, then transferred by road to the Planetary Materials Curatorial facility at Johnson Space Center in Houston to begin analysis. NASA officials claimed "prudence" dictated that the materials be transferred in secrecy, though no security threats were apparent.

Sample processing

Visible dust grains in the aerogel collector.

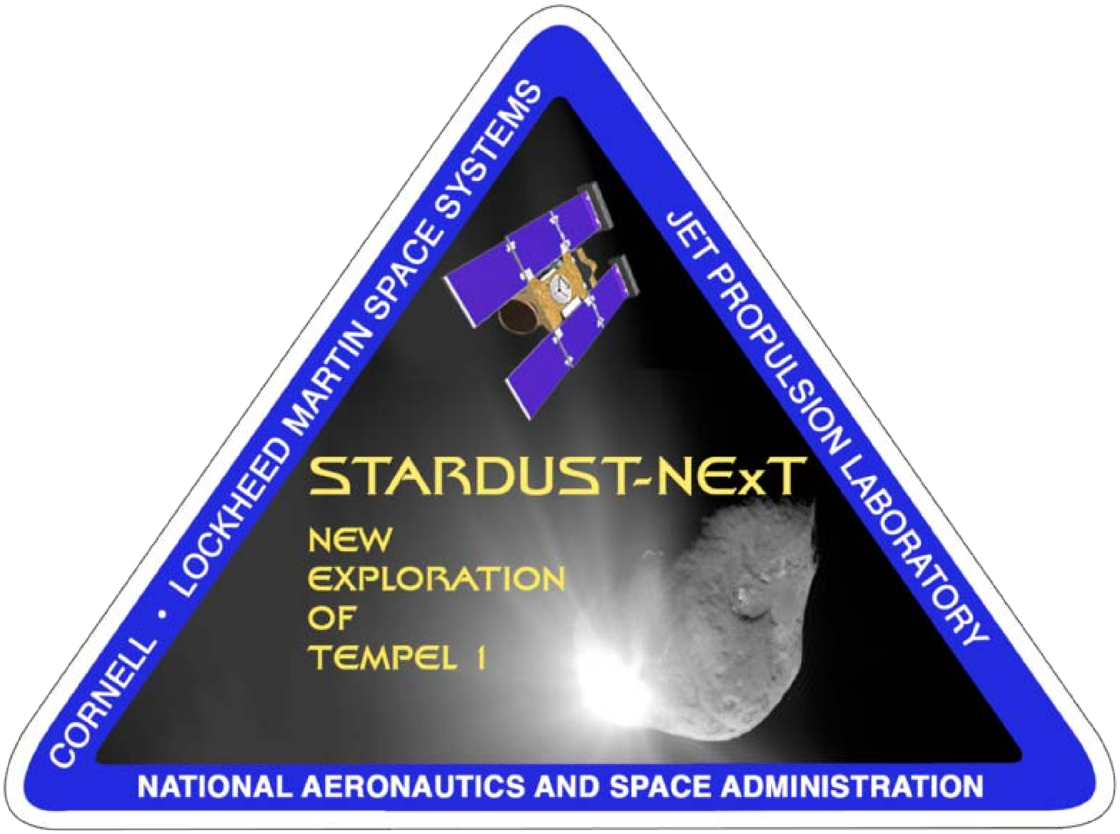
Visible track and particle in aerogel.

The sample container was taken to a clean room with a cleanliness factor 100 times that of a hospital operating room to ensure the star and comet dust was not contaminated. Preliminary estimations suggested at least a million microscopic specks of dust were embedded in aerogel collector. Ten particles were found to be at least 100 micrometers and the largest approximately 1000 micrometers. An estimated 45 interstellar dust impacts were also found on the sample collector, which reside on the back side of the cometary dust collector. Dust grains are being observed and analyzed by a volunteer team through the distributed computing project, Stardust@Home.

In December 2006, seven papers were published in the scientific journal, *Science*, discussing initial details of the sample analysis. Among the findings are: a wide range of organic compounds, including two that contain biologically usable nitrogen; indigenous aliphatic hydrocarbons with longer chain lengths than those observed in the diffuse interstellar medium; abundant amorphous silicates in addition to crystalline silicates such as olivine and pyroxene, proving consistency with the mixing of solar system and interstellar matter, previously deduced spectroscopically from ground observations; hydrous silicates and carbonate minerals were found to be absent, suggesting a lack of aqueous processing of the cometary dust; limited pure carbon (CHON) was also found in the samples returned; methylamine and ethylamine was found in the aerogel but was not associated with specific particles.

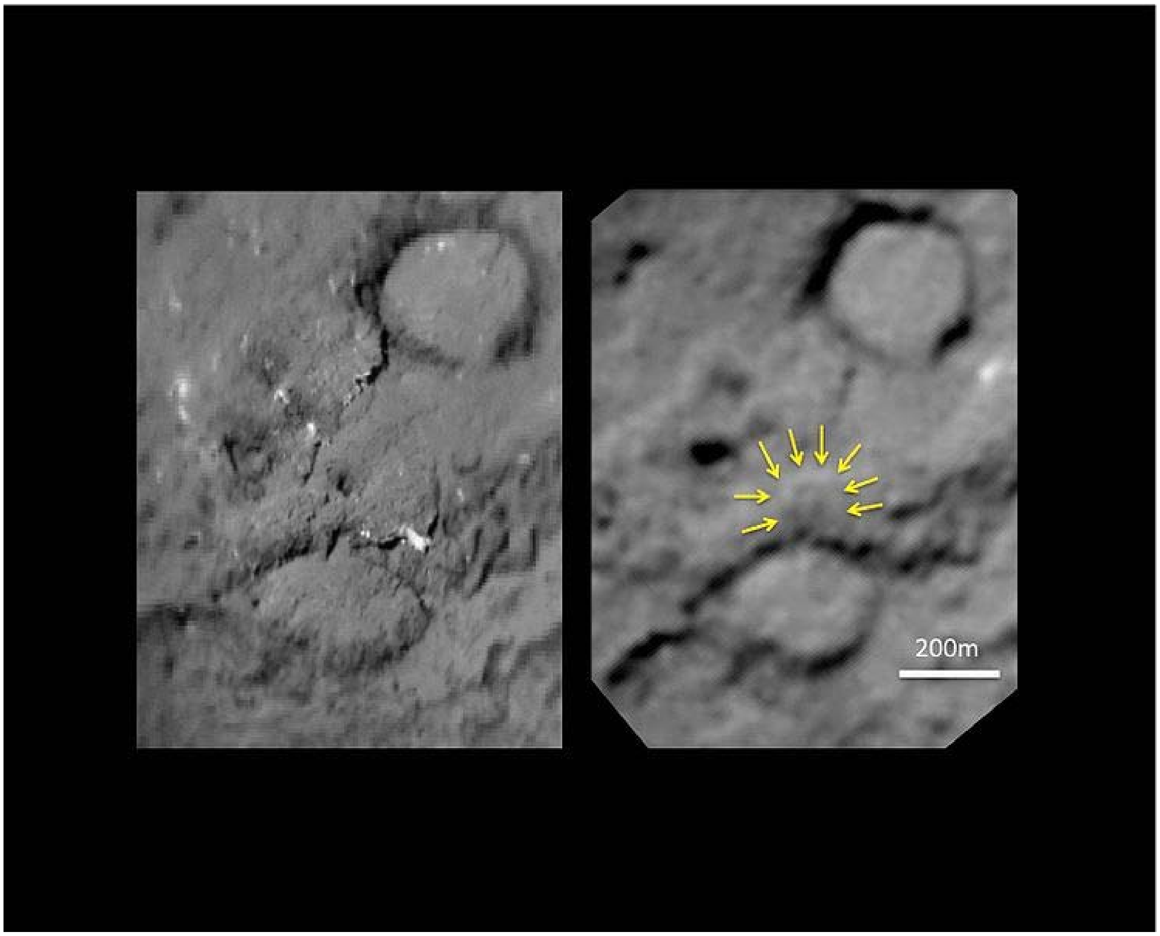
In 2010 Dr Andrew Westphal announced that Stardust@home volunteer Bruce Hudson found a track (labeled "I1043,1,30") among the many images of the aerogel which may contain an interstellar dust grain. The program allows for any volunteer discoveries to be recognized and named by the volunteer. Hudson named his discovery, *Orion*.

New Exploration of Tempel 1 (NExT)



On March 19, 2006, Stardust scientists announced that they were considering the possibility of redirecting the spacecraft on a secondary mission to image Tempel 1. The comet was previously the target of the Deep Impact mission in 2005, sending an impactor into the surface. The possibility of this extension could be vital for gathering images of the impact crater Deep Impact was unsuccessful in capturing due to dust from the impact, obscuring the surface.

Tempel 1 from the Stardust-NExT spacecraft during closest approach.



'Before and after' comparison images of Tempel 1 by *Deep Impact* (*left*) and *Stardust* (*right*).

On July 3, 2007 the mission extension was approved and renamed *New Exploration of Tempel 1* (NExT). This investigation will provide the first look at the changes to a comet nucleus produced after a close approach to the sun. NExT also will extend the mapping of Tempel 1, making it the most mapped comet nucleus to date. This mapping will help address the major questions of comet nucleus geology. The flyby mission was expected to consume the remaining fuel, signaling the end of the operability for the spacecraft.

The mission objectives included the following:

Primary objectives

- Extend the current understanding of the processes that affect the surfaces of comet nuclei by documenting the changes that have occurred on comet Tempel 1 between two successive perihelion passages, or orbits around the sun.
- Extend the geologic mapping of the nucleus of Tempel 1 to elucidate the extent and nature of layering, and help refine models of the formation and structure of comet nuclei.

- Extend the study of smooth flow deposits, active areas and known exposure of water ice.

Secondary objectives

- Potentially image and characterize the crater produced by Deep Impact in July 2005, to better understand the structure and mechanical properties of cometary nuclei and elucidate crater formation processes on them.
- Measure the density and mass distribution of dust particles within the coma using the Dust Flux Monitor Instrument instrument.
- Analyze the composition of dust particles within the coma using the Comet and Interstellar Dust Analyzer instrument.

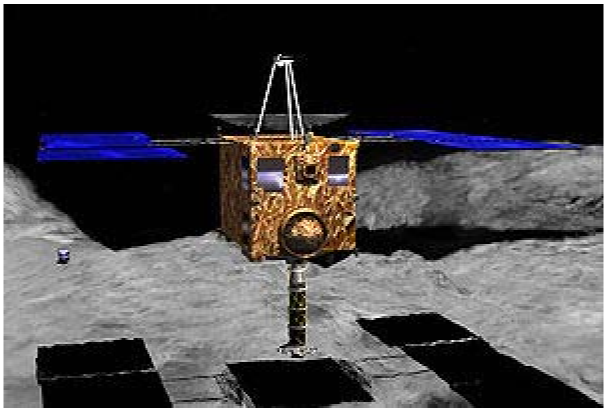
Encounter with Tempel 1

On February 15, 2011, at 04:42:00 UTC, Stardust-NExT encountered Tempel 1 from a distance of 181 km (112 mi). An estimated 72 images were acquired during the encounter. These showed changes in the terrain and revealed portions of the comet never seen by Deep Impact. The impact site from Deep Impact was also observed though it was barely visible due to material settling back into the crater.

Chapter- 5

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 minilander, 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 replica of the re-entry capsule exhibited at JAXAi (closed on December 28, 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
Sample obtained for Analysis	500 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 SF_{36}, 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 SF_{36}. 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 SF_{36}, to offer the name after Hideo Itokawa, and on 6 August, Minor Planet Circular reported that the target asteroid 1998 SF_{36} 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. (Close-up video)

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 Sagamihara 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.

Chapter- 6

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, 181 days ago)
Launch vehicle	Delta II 7925H

Launch site	Space Launch Complex 17B Cape Canaveral Air Force Station
Mission duration	In Transit Mars flyby *(completed 2009-02-04)*
COSPAR ID	2007-043A
Homepage	dawn.jpl.nasa.gov
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.

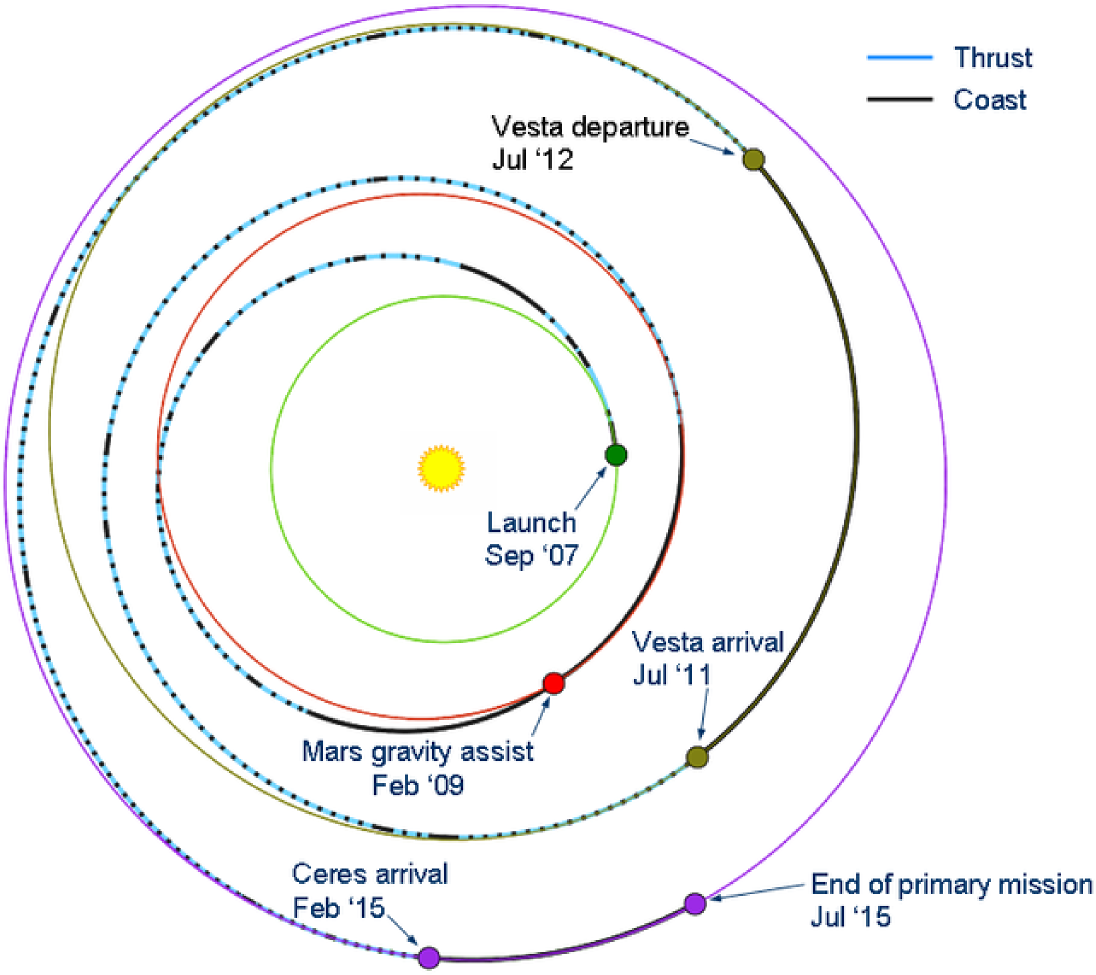
Dawn made its closest approach (549 km) to Mars on February 17, 2009 during a successful gravity assist. On this day the spacecraft placed itself in safe mode resulting in some data acquisition loss. The spacecraft was reported to be back in full operation two days later with no impact to the subsequent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

Mission

Dawn mission patch

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.



Planned flight trajectory

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

- 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.

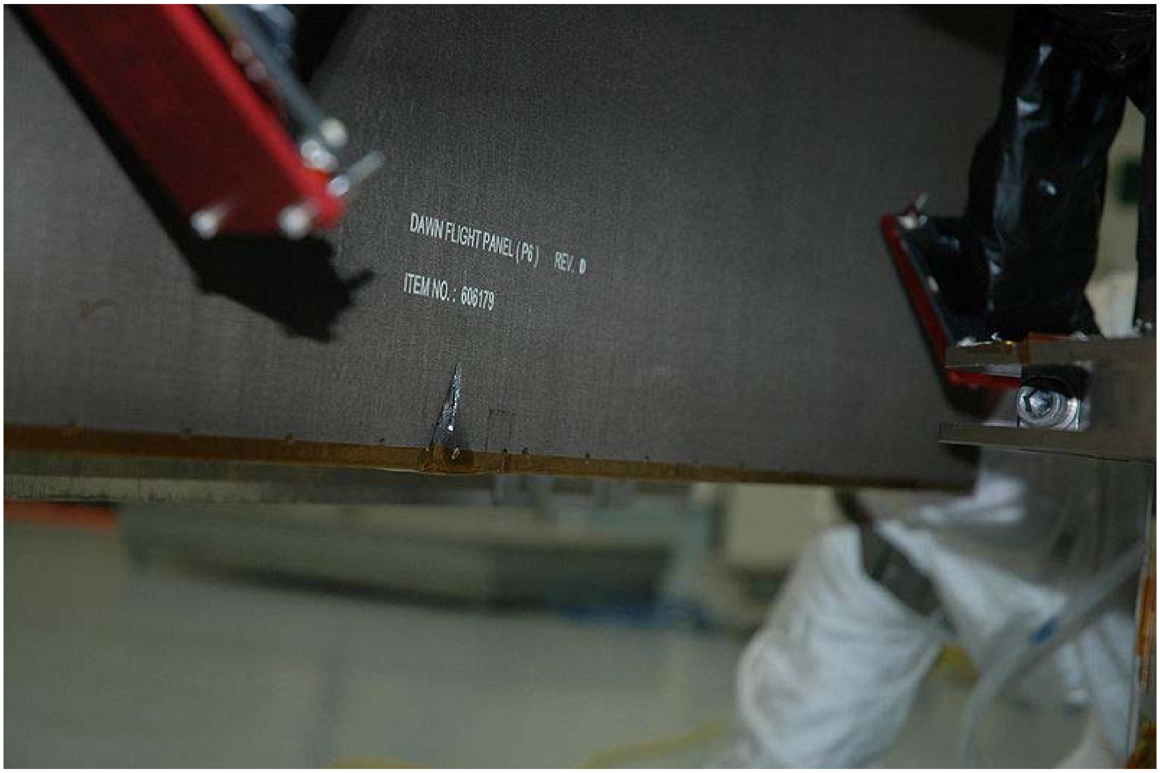
The IAU adopted a new definition of planet on August 24, 2006, and thus, if the IAU's definition stands and the spacecraft experiences no delays, *Dawn* will become the first mission to study a dwarf planet, arriving at Ceres five months prior to the arrival of *New Horizons* at Pluto.

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.