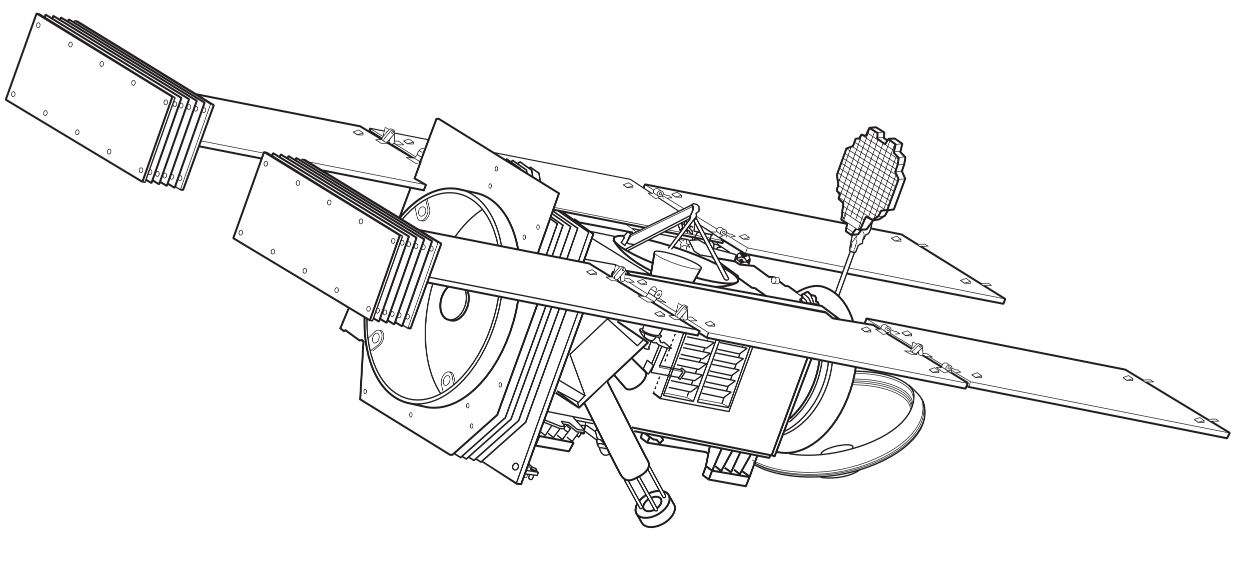
National Aeronautics and Space Administration

Stardust
Sample Return

Press Kit
January 2006



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GENERAL RELEASE:

NASA PREPARES FOR RETURN OF INTERSTELLAR CARGO

NASA's Stardust mission is nearing Earth after a 2.88 billion mile round-trip journey to return cometary and interstellar dust particles back to Earth. Scientists believe the cargo will help provide answers to fundamental questions about comets and the origins of the solar system.

The velocity of the sample return capsule, as it enters the Earth's atmosphere at 28,860 mph, will be the fastest of any human-made object on record. It surpasses the record set in May 1969 during the return of the Apollo 10 command module. The capsule is scheduled to return on Jan. 15.

"Comets are some of the most informative occupants of the solar system. The more we can learn from science exploration missions like Stardust, the more we can prepare for human exploration to the moon, Mars and beyond," said Mary Cleave, associate administrator for NASA's Science Mission Directorate.

Several events must occur before scientists can retrieve cosmic samples from the capsule landing at the U.S. Air Force Utah Test and Training Range, southwest of Salt Lake City. Mission navigators will command the spacecraft to perform targeting maneuvers on Jan. 5 and 13. On Jan. 15 at 12:57 a.m. EST, Stardust will release its sample return capsule. Four hours later, the capsule will enter Earth's atmosphere 410,000 feet over the Pacific Ocean.

The capsule will release a drogue parachute at approximately 105,000 feet. Once the capsule has descended to about 10,000 feet, the main parachute will deploy. The capsule is scheduled to land on the range at 5:12 a.m. EST.

After the capsule lands, if conditions allow, a helicopter crew will fly it to the U.S. Army Dugway Proving Ground, Utah, for initial processing. If weather does not allow helicopters to fly, special off-road vehicles will retrieve the capsule and return it to Dugway. Samples will be moved to a special laboratory at NASA's Johnson Space Center, Houston, where they will be preserved and studied.

"Locked within the cometary particles is unique chemical and physical information that could be the record of the formation of the planets and the materials from which they were made," said Don Brownlee, Stardust principal investigator at the University of Washington, Seattle.

NASA expects most of the collected particles to be no more than a third of a millimeter across. Scientists will slice these particle samples into even smaller pieces for study.

The Jet Propulsion Laboratory, Pasadena, Calif. manages the Stardust mission for NASA's Science Mission Directorate, Washington. Lockheed Martin Space Systems, Denver, developed and operates the spacecraft.

For information about the Stardust mission on the Web, visit:

http://www.nasa.gov/stardust

For information about NASA and agency programs on the Web, visit:

http://www.nasa.gov/home

- end of general release -

Media Services Information

NASA Television Transmission

The NASA TV Media Channel is available on an MPEG-2 digital C-band signal accessed via satellite AMC-6, at 72 degrees west longitude, transponder 17C, 4040 MHz, vertical polarization. In Alaska and Hawaii, it's available on AMC-7 at 137 degrees west longitude, transponder 18C, at 4060 MHz, horizontal polarization. A Digital Video Broadcast compliant Integrated Receiver Decoder is required for reception. For digital downlink information for NASA TV's Media Channel, access to NASA TV's Public Channel on the Web and a schedule of programming for Stardust activities, visit **http://www.nasa.gov/ntv**.

Media Credentialing

News media representatives who wish to cover the Stardust's return to Earth on location at the U.S. Army Dugway Proving Ground in Utah must be accredited through Dugway's Public Affairs Office. Journalists may phone the office at (435) 831-3409.

Briefings

News briefings will be held at the U.S. Army Dugway Proving Ground before and after the encounter. Information about upcoming briefings will be available on the Internet as noted below.

Internet Information

More information on the Stardust mission, including an electronic copy of this press kit, press releases, fact sheets, status reports and images, can be found at **http://www.nasa.gov/stardust**. Extensive information on the Stardust project including an electronic copy of this press kit, press releases, fact sheets, status reports, briefing schedule and images, is available from the Stardust project homepage, **http://stardust.jpl.nasa.gov**.

Quick Facts

Spacecraft

Dimensions: Main structure 1.7 meters (5.6 feet) high, 0.66 meter (2.16 feet) wide, 0.66 meter (2.16 feet) deep; length of solar arrays 4.8 meters (15.9 feet) tip to tip; sample return capsule 0.8 meter (32 inches) diameter and 0.5 meter (21 inches) high

Weight: 385 kg (848 lbs) total at launch, consisting of 254-kilogram (560-pound) spacecraft and 46-kilogram (101-pound) return capsule, and 85 kilograms (187 pounds) fuel

Power: Solar panels providing from 170 to 800 watts, depending on distance from Sun

Mission Milestones

Launch: Feb. 7, 1999 from Cape Canaveral Air Force Station, Fla.
Launch vehicle: Delta II (model 7426) with Star 37 upper stage
Earth-comet distance at time of launch: 820 million kilometers (508 million miles)
Interstellar dust collection: Feb. 22-May 1, 2000; Aug. 5-Dec. 9, 2002
Earth gravity assist flyby: Jan. 15, 2001
Altitude at Earth gravity assist: 6,008 kilometers (3,734 miles)
Asteroid Annefrank flyby: Nov. 2, 2002
Comet Wild 2 encounter: January 2, 2004
Number of pictures of comet nucleus taken during encounter: 72
Earth-comet distance at time of encounter: 389 million kilometers (242 million miles)
Total distance traveled Earth to comet: 3.41 billion kilometers (2.12 billion miles)
Spacecraft speed relative to comet at closest approach: 22,023 km/h (13,684 mph)
Earth return: Jan. 15, 2006
Landing site: Utah Test & Training Range
Velocity of sample return capsule entering Earth's atmosphere: 46,440 km/h (28,860 mph) -- fastest reentry of spacecraft in history
Total distance traveled comet to Earth: 1.21 billion kilometers (752 million miles)
Total distance traveled entire mission (Earth to comet to Earth): 4.63 billion kilometers (2.88 billion miles)

Program

Cost: $168.4 million total (not including launch vehicle), consisting of $128.4 million spacecraft development and $40 million mission operations

Mission Overview

Launched in 1999, the Stardust spacecraft has circled the Sun a total of three times over seven years. On the way to its comet encounter, it collected interstellar dust on two different solar orbits. On Jan. 2, 2004, Stardust flew past the nucleus of comet Wild 2 at a distance of 240 kilometers (149 miles). During this close flyby, a special collector captured particles of the comet as the spacecraft flew through the coma, or cloud of dust and debris, surrounding Wild 2.

Two years and 13 days after this first-of-its-kind cometary sample mission, the Stardust spacecraft will eject a capsule that will descend into the Department of Defense's Utah Test & Training Range carrying the mission's cosmic booty of cometary and interstellar dust samples.

Stardust's trajectory was calculated to allow the spacecraft to fly past Wild 2 at a relatively low speed at a time when the comet is active -- but not too active. The trajectory also minimized the energy needed to launch the spacecraft, allowing for a smaller, less expensive launch vehicle; maximized the time for favorable collection of interstellar dust; and made the spacecraft approach Earth at a relatively low speed when it returns.

Launch

Stardust began its voyage on Feb. 7, 1999 from Space Launch Complex 17A at Cape Canaveral Air Station, Fla., on a variant of the Delta II launch vehicle known as a Delta 7426, one of a new series of rockets procured under NASA's Med-Lite program.

Launch events occurred in three phases. First, the Delta lifted off and entered a 185-kilometer-high (115-mile) parking orbit; then it coasted for about a half-hour; and finally an upper-stage engine fired to send Stardust out of Earth orbit.

Cruise

Stardust's first two years of flight carried it on the first of its three orbital loops around the Sun. In January 2000, when Stardust was between the orbits of Mars and Jupiter -- the most distant point from the Sun that it reached during that orbit -- the spacecraft's thrusters fired to place it on course for a later gravity assist swingby of Earth.

As Stardust traveled back inward toward the Sun, it collected interstellar particles flowing through the solar system. From February through May 2000, the spacecraft deployed its collector to capture these interstellar particles. One part of the collector mechanism called its "B side" faced the incoming interstellar dust stream, while the back side, called the "A side," was later used for the spacecraft's dust collection at comet Wild 2.

The spacecraft completed its first solar orbit when it flew by Earth on Jan. 15, 2001. The flyby altitude at its closest approach distance was approximately 6,008 kilometers (3,773 miles). The effect of Earth's gravity increased the size of Stardust's orbit so that it circled the Sun once each 2-1/2 years, and placed it on a flight path leading to an intercept of its quarry, comet Wild 2.

Beginning in August 2002, as the spacecraft traveled back inward toward the Sun on the later part of its second orbit, Stardust again exposed the "B side" of its collector to interstellar particles flowing through the solar system. It continued to collect interstellar particles until December 2002. The total time it spent collecting interstellar particles over the entire mission was 195 days.

During this second period collecting interstellar particles, Stardust flew within 3,100 kilometers (1927 miles) of asteroid Annefrank. This encounter took place on Nov. 2, 2002, and was used as a test of ground and spacecraft operations later put into practice during the comet encounter.

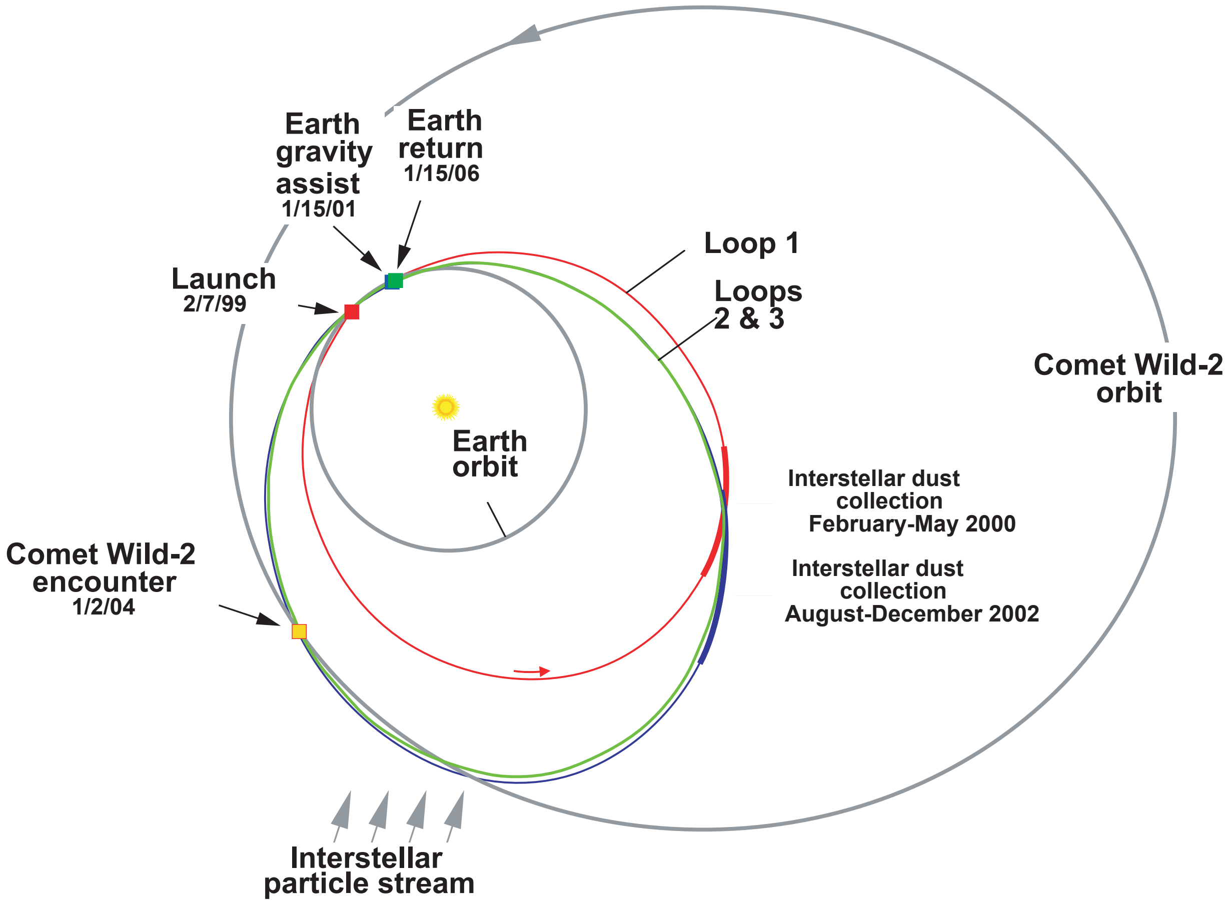
Comet Flyby

The chain of events leading up to comet encounter began nine days out when Stardust deployed its "cometary catcher's mitt," a tennis-racket-shaped particle catcher featuring more than 1,000 square centimeters (160 square inches) of collection area filled with a material called aerogel. Made of pure silicon dioxide -- the same as sand or glass -- aerogel is a thousand times less dense than glass because it is 99.8 percent air. The high-tech material has enough "give" in it to slow and stop particles without altering them radically.

Stardust entered the comet's coma -- the vast cloud of dust and gas that surrounds a comet's nucleus -- on December 31, 2003. From that point on it kept its defensive shielding between it and the stream of cometary particles it would fly through.

On Jan. 2, 2004, at 11:40 a.m. PST (2:40 p.m. EST), after traveling 3.41 billion kilometers (2.12 billion miles) across the solar system over four years -- the Stardust spacecraft made its closest approach of comet Wild 2 at a distance of 240 kilometers (149 miles). During this close encounter, the faster-moving comet actually hurtled past the slower Stardust at a relative speed of 22,023 kilometers per hour (13,684 miles per hour). In terrestrial terms such velocity is guaranteed to smoke any police officer's radar gun, but in cosmic terms such relative speed between spacecraft and comet is relatively leisurely, allowing Stardust to "soft-catch" samples of comet dust without changing them greatly.

In the hours and days following the encounter, images and other science and engineering data recorded onboard during the event were transmitted to Earth.



Mission trajectory

The Stardust team expected to see a uniform increase in the number of particles as the spacecraft approached the comet, then a reduction as it pulled away. Instead, onboard instruments indicated Stardust flew through a veritable swarm of particles, followed by a gap with almost nothing, and then another swarm. Data indicated that as the spacecraft flew through sheets of comet particles, on at least 10 occasions the first layer of its shielding was breached. (Despite this thumping by comet particles, telemetry indicates Stardust is in excellent shape as it closes in now on Earth.)

As particles impacted the spacecraft at 6.1 kilometers per second (3.8 miles per second), onboard instruments performed near-instantaneous analysis of some samples. Other particles were stored onboard for return to Earth.

During Stardust's passage of the most concentrated region of cometary particles, its dust flux monitor instrument logged into the spacecraft's computer memory measures of the size and frequency of dust particle hits. At the same time, the comet and interstellar dust analyzer performed instantaneous compositional analysis of material and also stored its results in the spacecraft's onboard memory.

Along with this cosmic taste testing, the spacecraft also took some remarkable images of comet Wild 2's nucleus. The otherworldly landscape included such features as steep, near vertical cliffs; house-size boulders; pinnacles; flat-floored craters with near vertical walls; haloed pit craters; overhangs and materials with varying brightness. The images of Wild 2 showed a complex rugged surface that is quite different from those of other comets, asteroids and moons that have been imaged. The deep depressions on the comet suggest that regions of the surface have eroded to depths of 100 meters or more. One of the most spectacular findings was the comet had more than 20 active jets, localized hotspots, spewing gas and dust into space.

Six hours after the comet encounter, the spacecraft carried out a half-hour process of retracting and stowing the sample collector with its cometary pickings. From that point on, the sample canister was to remain sealed until it is opened in a cleanroom at NASA's Johnson Space Center a few days following Earth return in January 2006.

Deep Space Navigation

To bring the spacecraft from beyond Earth's orbit to a predetermined landing zone on Earth, navigators will use techniques that have legacies in the Apollo missions of the 1960s and 1970s – as well as the return of the Genesis spacecraft's solar wind samples in 2004. The Stardust navigation team must know the spacecraft's position and speed precisely -- and for this, they call upon the giant dishes of NASA's Deep Space Network. Navigators analyze the spacecraft's radio signal using techniques called radiometric and Doppler tracking to help pinpoint its distance from Earth as an aid to navigation.

Throughout the Stardust mission, tracking and telecommunications have been provided by NASA's Deep Space Communication Complexes in California, Australia and Spain. The data rate from the spacecraft ranges from 1 to 33 kilobits per second. Most data from the spacecraft are received by the Deep Space Network's 34-meter-diameter (110-foot) antennas, but 70-meter (230-foot) antennas have also occasionally been used.

Earth Return

For planning purposes, the mission has defined Earth return as the time period from entry minus 90 days until the sample return capsule enters Earth's atmosphere. The location of the landing footprint for the capsule will be predicted by tracking the spacecraft before capsule release. Since the capsule does not have a propulsion system, there is no way to abort the entry sequence following its release.

The capsule will arrive at the top of Earth's atmosphere at an altitude of 125 kilometers (410,000 feet) on Jan. 15 at 2:57 a.m. Mountain Standard Time (MST). Mission navigators are targeting the capsule to land within an ellipse 76 by 44 kilometers (47 by 27 miles) around a target point within the Utah Test & Training Range.

Three trajectory correction maneuvers were planned during the final 90 days of approach. The first was performed on Nov. 16, 2005. Two more are scheduled Jan. 5 and Jan. 13, 2006. If mission navigators feel another thruster firing is required to place the Stardust sample return capsule within its designated re-entry corridor, a final "contingency maneuver" may be performed Jan. 14.

At about 7 a.m. MST Jan. 14, the Stardust team will conduct one final teleconference to discuss the status of the spacecraft's trajectory. If all is "go," they will radio the spacecraft to start executing a series of commands to release the sample return capsule.

Backup Orbit

As the spacecraft approaches Earth, the Stardust team will closely evaluate its trajectory. If at any point navigators and mission planners feel the spacecraft and/or its sample return capsule are not on target, they can go to "plan B" -- a backup orbit. Under this plan, ground controllers will command the spacecraft to fire its thrusters to place itself and its capsule in a 3.5- to 4-year backup orbit around the Sun to come back to Earth. If required, the maneuver to place the spacecraft and capsule in this temporary orbit would take place at entry minus 3.7 hours. This backup orbit could allow for another opportunity for the capsule to land at the Utah Test & Training Range 3.5 to 4 years later.

Sample Return Capsule Release

On Jan. 14 at 10:57 p.m. MST -- when the spacecraft is 110,728 kilometers (68,805 miles) from Earth -- Stardust will release its sample return capsule. Two cable cutters are fired to sever the cable harness connecting the capsule to the spacecraft, after which three retention bolts are also fired to sever the connection between the capsule and the spacecraft bus. A separation spin mechanism pushes the capsule away and simultaneously spins it at 14 to 16 revolutions per minute. This spin helps to stabilize the capsule's orientation, or "attitude."

About 15 minutes after separation, the main spacecraft will fire its thrusters in a divert maneuver to keep it from hitting Earth. This maneuver will put the Stardust spacecraft in an orbit around the Sun. The now-free-flying sample return capsule will continue streaking toward Earth on a purely ballistic trajectory that will take it into Earth's atmosphere four hours later.

Atmospheric Entry

At 2:57 a.m. MST, the capsule will enter Earth's atmosphere at an altitude of 125 kilometers (410,000 feet). (Note: This and other altitudes are expressed as distances above mean sea level. The elevation at the Utah Test & Training Range is about 1,220 meters (4,000 feet), so this amount should be subtracted from any altitude figure to get a more precise distance above the ground.)

At this point, the capsule will be about 886 kilometers (551 miles) from its landing zone in Utah, moving at a velocity of about 12.8 kilometers per second (28,600 miles per hour). This will be the fastest human-made object to enter Earth's atmosphere. In second place was the Apollo 10 command module, which entered at a speed of 11.11 kilometers per second (24,861 mph).

Within minutes of entering the atmosphere, the radar and other tracking assets at the Utah Test & Training Range are expected to acquire the incoming capsule. By entry plus 38 seconds, the capsule will have already covered half the horizontal distance to its landing zone. At this point, aerodynamic friction will raise the temperature of the capsule's heat shield, making infrared tracking a possibility. At entry plus 52 seconds and at an altitude of 61 kilometers (200,000 feet), the capsule will experience peak heating. At this point, the temperature on the exterior of the heat shield will spike at 185 Celsius (365 Fahrenheit). Ten seconds later, peak deceleration will occur as the slowing capsule experiences 38 times the force of gravity (or 38 G's).

Drogue Chute Deploy

At entry plus 116 seconds, the capsule's deceleration will ease off to 3 G's, which will initiate a timer. About 16 seconds later, the capsule's avionics will command a mortar to fire, deploying a drogue parachute. The sample return capsule is now at an altitude of 32 kilometers (20 miles), and nearly overhead of its landing zone. The drogue parachute is deployed when the capsule is traveling at a supersonic speed (about mach 1.4).

At about entry plus 3 minutes and at an altitude of 24 kilometers (15 miles), the capsule will begin its vertical descent over the Utah Test & Training Range. At about entry plus 4 minutes, the capsule will enter the range's special-use airspace at an altitude of 17 kilometers (11 miles).

Utah Test & Training Range

The Utah Test & Training Range provides the largest overland contiguous block of restricted airspace in the continental United States authorized for supersonic flight, available for aircrew training and weapons testing. The airspace, situated over 6,796 square kilometers (2,624 square miles), is under the jurisdiction of the U.S. Air Force. The remainder is managed by the U.S. Army at Dugway Proving Ground. Airspace boundaries do not necessarily coincide with the boundaries of the Defense Department land beneath the airspace.

Operated and maintained by the 388th Range Squadron based out of Hill Air Force Base some 50 miles to the east, the Utah Test & Training Range supports training for all branches of the armed services and their allies with capabilities for air-to-ground, air-to-air and ground force exercises. More than 22,000 training sorties and more than 1,000 test sorties are flown out on the range annually. It is used for testing munitions and propellants up to the most powerful ICBM rocket motors and non-nuclear explosive components.

The Air Force range is supporting Stardust by providing range imagery and targeting guidance. The range's mission control center -- located at Hill Air Force Base -- will radio information to the helicopter crews. An Air Force building at the Army's Michael Army Air Field will be home to the cleanroom erected to temporarily house the Stardust capsule after it is captured.

Dugway Proving Ground

The U.S. Army's Dugway Proving Ground serves as the nation's chemical and biological defense proving ground. It is a large, remote, closed post on the high desert that employs about 1,200 military, government civilians and support contractors. Dugway's mission is to test U.S. and allied biological and chemical defense systems; perform nuclear-biological-chemical survivable testing of defense material; provide support to chemical and biological weapons conventions; and operate and maintain an installation to support test missions.

Dugway is supporting Stardust by providing facilities, logistical, weather and range expertise as well as security and support personnel. The majority of the events surrounding the Stardust return will occur at the facility's Ditto Test Area which approximately 19 kilometers (12 miles) from the installations main gate. Located in Ditto is the Michael Army Air Field, where the Stardust recovery helicopters will be based.

Dugway is located approximately 130 kilometers (about 80 miles) west-southwest of Salt Lake City, in the Great Salt Lake Desert in Tooele County, Utah. The Dugway Proving Ground covers 3,233 square kilometers (1,248 square miles) -- larger than the state of Rhode Island. Surrounded on three sides by mountain ranges, the proving ground's terrain includes mountains, valleys and a large, flat, sparsely vegetated area that extends westward into the southern reaches of expansive salt flats of the Great Salt Lake Desert.

Main Chute Deploy

After descending into the Utah Test & Training Range's controlled airspace on its drogue parachute, when it reaches an altitude of about 3 kilometers (10,000 feet), the capsule will cut one of the lines holding the drogue chute. This in turn will allow the drogue to pull out a larger parachute. At the same time the capsule will activate its UHF locator beacon, transmitting through a single antenna located in a leg of the main chute's bridle. The UHF antenna remains with the sample return capsule after ground impact. Batteries powering the UHF have enough capacity to operate the beacon for 20 hours.

Touchdown

The Stardust capsule will touch down at about 3:12 a.m. MST. When it reaches the ground, the capsule will be traveling at approximately4.5 meters (14.8 feet) per second, or about 16 kilometers per hour (10 miles per hour). When the impact of landing is sensed, a cutter will release the main chute from the capsule. This will prevent the main chute from dragging the capsule across the desert.

The landing footprint for the sample return capsule is about 44 by 76 kilometers (27 by 47 miles), an ample space to allow for aerodynamic uncertainties and winds that might affect the direction the capsule travels in the atmosphere.

Sample Return Capsule Ground Recovery

The primary goal of landing site operations is to preserve the condition of the interior of the science canister, and the cleanliness and physical integrity of the canister itself. Helicopters and vehicles will approach the capsule from a crosswind direction to avoid potential contamination of the capsule

Even before the capsule touches down, personnel tracking it will provide intercept vectors or advisories to the three recovery helicopters until sighting of the capsule by the ground recovery team is confirmed. In the event the helicopters are grounded due to poor weather, ground recovery teams will be dispatched and directed to the landing site.

When helicopters arrive at the site, one of them will land. An explosive ordnance disposal expert called the on-scene commander, or "Oscar," will conduct a sweep of the area for any unexploded ordinance from other programs at the test range, while the recovery team's safety lead visually evaluates the condition of the capsule. Photographs will be taken of the capsule before moving it from its landed condition. After verifying that the capsule's state is nominal, personnel will prepare the capsule for stowage in the helicopter.

Given the capsule's small size and mass (about 43 kilograms (95 pounds)), mission planners do not expect that recovering and moving it will require extraordinary handling measures or hardware other than a specialized handling fixture to cradle the capsule during transport. Using three people, the capsule will be lifted by the edges of its heat shield (no special handling attach points are designed on the capsule), and any significant mud will be removed from the capsule.

Following a normal entry, the capsule will be hand-carried to the helicopter for transport. The capsule will be warm; temperature of the heat shield could be as high as 60

Celsius (140 Fahrenheit), so handlers will be required to wear protective gloves. After any mud is removed, the capsule will be double-bagged and lowered onto a handling fixture. If in close proximity, the parachute will be recovered and preserved for analysis.

Cleanroom

Once the capsule is onboard, the helicopter will fly it to a hangar at Michael Army Air Field. Here the capsule will be transferred from the helicopter to a truck, secured and then transported to an adjacent building, where scientists and engineers will be waiting in a temporary cleanroom. By this time, the capsule's heat shield is expected to have passively cooled to 25 Celsius (75 Fahrenheit).

In the temporary cleanroom, the sample canister will be removed from the capsule and connected to a purge system that feeds it with a constant flow of ultra-pure gaseous nitrogen. Time-critical events will conclude when the purge is in place.

The capsule, sample canister and associated hardware will then be prepared for travel by aircraft to NASA's Johnson Space Center in Texas.

Bad Weather Recovery Operations

To insure the recovery of the capsule in the event poor weather grounds the helicopters, two ground vehicles outfitted with all-terrain rubber tracks in place of wheels will be staged outside the predicted landing footprint the day before landing. After the capsule has landed and tracking personnel have determined the most likely landing point, target coordinates will be communicated via radio to the recovery crew in the ground vehicles.

The vehicles will then converge upon the coordinates while monitoring the capsule's UHF beacon frequency. Once the capsule has been located, it will be handled in accordance with the nominal recovery procedures, placed into the vehicle and transported to a rendezvous point at the nearest road where the capsule can be transferred into a wheeled truck. From that point, the capsule is transported to the hangar at Michael Army Air Field and handled in accordance with the nominal plan.

Sample Curation

A dedicated handling and curation lab for the Stardust samples was prepared within the past two years at NASA's Johnson Space Center, Houston, Texas. The lab has new, specially designed equipment to optically scan the aerogel and locate captured grains within it. It is also outfitted with a new generation of equipment to section aerogel and extract grains for later preliminary analysis in laboratories all over the world.

The lab is a Class 100 cleanroom in the same building that houses NASA's astromaterials collections including stratospheric dust particles, Antarctic meteorites, Moon rocks and solar wind samples. In a Class 100 cleanroom, no more than 100 particles larger than 0.5 microns are present in any given cubic foot of air. By comparison, a typical hospital operating room is Class 10,000 (10,000 such particles per cubic foot of air).

Once safely in the lab, the canister will be opened and the aerogel and its comet and interstellar dust harvest will be inspected. The capsule contents, including the aerogel and contained samples, must be maintained at a Class 100 clean-room environment or better during this process. Continuous particle counters and "witness plates" that keep a record of any particulate and non-volatile residue will be used to monitor the environment during all times the aerogel is open to the laboratory air. When not under examination, the samples are stored in clean, dry nitrogen gas.

About six months of preliminary investigation by a dedicated team will precede release of the Stardust samples to the general analysis community. This preliminary investigation period has the goal of documenting the state of the collected sample, identifying the range of samples present, assessing the best way to proceed with general sample distribution and analysis, and answering a few key questions about comets and the birth of the solar system.

The largest particle collected is expected to be nearly a millimeter across, but most particles from a comet are smaller than the diameter of a human hair. While the mission will return about a million dust particles, the total mass of the sample returned by Stardust will probably be about 1 milligram. Though this sample quantity could seem small, to cometary scientists this celestial acquisition is nearly an embarrassment of riches. Abundant evidence indicates that solid samples from both cometary and interstellar sources are very fine-grained, most of them on the scale of a micron (1/100th the diameter of a human hair) or smaller. Because the Stardust science team is focused on these grains, they do not require a large sample mass. A single 100-micron cometary particle could be an aggregate composed of millions of individual interstellar grains. The key information in these samples is retained at the micron level, and even aggregates of 10 microns in size are considered giant samples -- so large, in fact, that they have to be sliced or otherwise subdivided for many of the analytical investigations.

Planetary Protection

The United States is a signatory to the United Nations' 1967 Treaty of Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies. Known as the "Outer Space Treaty," this document states in part that exploration of the Moon and other celestial bodies shall be conducted "so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." Stardust has been evaluated by NASA's planetary protection officer to be appropriate for an "unrestricted" Earth return, meaning its sample is considered safe to Earth's biosphere and inhabitants, which is consistent with recommendations of the Space Studies Board of the National Research Council.

Comets are small, cold, primordial bodies that formed at the edge of the solar system, near Pluto. They are made of material that is nearly unchanged since the Sun and planets formed 4.6 billion years ago. Comets are frozen bodies, far from the Sun, that have never been exposed to the environments similar to those on the early Earth that preceded and led to the emergence of life. Comets are among the most inhospitable places in the solar system for life.

Comet dust is not considered to be a threat because it is a natural component of our environment. More than 30,000 tons of comet falls to Earth every year. In a single day, the state of California collects a billion times as many 10-micron cometary particles as the Stardust mission will return. This flux of outer solar system material has occurred for billions of years and may have even played a role in the evolution of life on our planet by bringing necessary organic compounds to Earth.

Names Microchips

The Stardust project sponsored a "Send Your Name to a Comet" campaign that invited people from around the world to submit their names via the Internet to fly onboard the Stardust spacecraft. Two microchips bearing the names of more than 1.1 million people are onboard the Stardust spacecraft.

The names were electronically etched onto fingernail-size silicon chips at a microdevices laboratory at NASA's Jet Propulsion Laboratory. The lettering on the microchips is so small that about 80 letters would equal the width of a human hair. The names can be read only with the aid of an electron microscope.

The first Stardust microchip contains 136,000 names collected in 1997 from persons all over the world. That microchip has been placed inside the sample return capsule. The second microchip contains more than a million names from members of the public, and was placed on the back of the arm that holds the dust collector. In addition to holding names from the public at large, the second microchip contains all 58,214 names inscribed on the Vietnam Veterans Memorial in Washington as a tribute to those who died in that war.

Recovery Timeline - Nominal Conditions

Jan. 15, 2006

Time	*Event Description*
G - 120 min	Recovery teams briefed on expected weather conditions and staging areas
G - 90 min	Recovery teams receive authorization to execute recovery operations
G - 30 min	Teams board helicopters and engines begin run-up
G - 25 min	Helicopter recovery teams lift off and fly to staging area outside landing ellipse
G - 5 min	Helicopters begin vectoring towards capsule under range control, from above and upwind of the capsule
G - 0	Capsule landing determined by tracking; location of site provided to recovery team and recovery command system. First helicopter begins vectoring toward capsule location, with others following behind
G + 10 min	First helicopter arrives at capsule - On-scene commander and safety expert debark, helicopter lifts off to provide overhead lighting - Initial unexploded ordnance assessment complete - safe approach route to capsule defined - Initial capsule safety assessment complete - Landing locations for other helicopters determined and marked
G + 15 min	Second helicopter arrives and lands. Additional recovery team members cleared to proceed to capsule
G + 20 min	Capsule safety inspection completed - Capsule's structural integrity assessed - Capsule vents cleared of any obstructions, material bagged - Sulphur dioxide, acetonitrile, hydrogen cyanide, carbon monoxide monitored at capsule - Safety keep-out zones (if any) marked with flags - Gas samples collected from vicinity of capsule's back-shell vents - Tape placed over both back-shell vents - Recovery team briefed on condition of capsule and approach route

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G + 30 min	Capsule field processing complete - Photos taken to document capsule's condition - Gas samples collected from vicinity of capsule - Three persons lift capsule, one person removes debris, material bagged - Capsule double-bagged with sulfur dioxide monitor - Capsule secured in handling fixture - Soil samples collected from impact and recovery sites
G + 45 min	Overhead helicopter lands - Capsule handling fixture secured in helicopter for transport
G + 75 min	Helicopter returns to air field with capsule
G + 90 min	Capsule manually transferred from helicopter to ground vehicle
G + 110 min	Ground transport vehicle arrives outside entrance to Building 1012 - Capsule transferred from vehicle to a point just outside entrance to building - Wearing half mask respirator, safety expert removes double bags from capsule - Any additional external debris removed and bagged - Building door opened; capsule transferred inside and placed on cleanroom holding fixture
G + 120 min	Capsule transferred into cleanroom - Photos taken
G + 130 min	Capsule processing begins - 6 bolts and parachute canister removed - 2 cables disconnected - Capsule purge connected - Heat shield material removed from back shell at 12 bolt locations - 12 back-shell bolts removed - 2 cables disconnected - Back shell removed - Canister's gaseous nitrogen purge connected - Capsule battery disconnected and removed - 6 bolts removed, sample canister extracted from heat shield - Verify no water dripping from filter - Avionics box disconnected and removed - All hardware bagged and secured in fixtures
G + 210 min	Environmental monitors attached to handling fixture; final photos taken of capsule/canister and back shell

Spacecraft

The Stardust spacecraft incorporates innovative, state-of-the-art technologies pioneered by other recent missions with off-the-shelf spacecraft components and, in some cases, spare parts and instrumentation left over from previous missions.

The Stardust spacecraft is derived from a rectangular deep-space bus called SpaceProbe developed by Lockheed Martin Space Systems, Denver, Colo. Total weight of the spacecraft, including the sample return capsule and propellant carried onboard for trajectory adjustments, is 385 kilograms (848 pounds). The main bus is 1.7 meters (5.6 feet) high, 0.66 meter (2.16 feet) wide and 0.66 meter (2.16 feet) deep, about the size of an average office desk. Panels are made of a core of aluminum honeycomb, with outer layers of graphite fibers and polycyanate face sheets. When its two parallel solar panels are deployed in space, the spacecraft takes on the shape of a letter H.

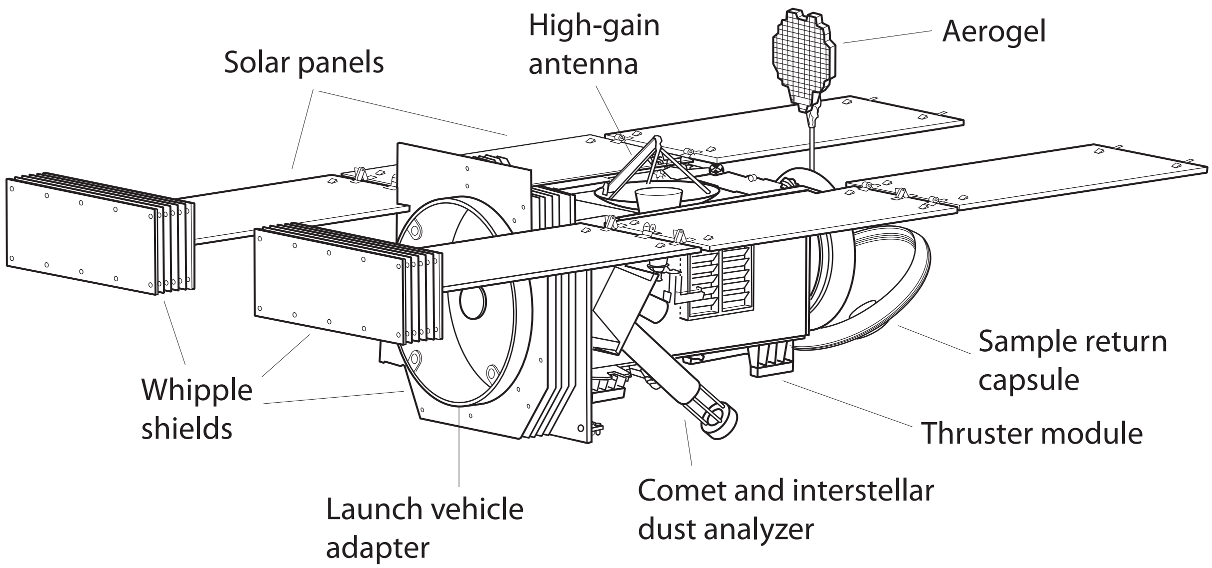
There are three dedicated science packages on Stardust -- the two-sided dust collector, the comet and interstellar dust analyzer, and the dust flux monitor. Science data is also be obtained without dedicated hardware. The navigation camera, for example, provided images of the comet both for targeting accuracy and scientific analysis.

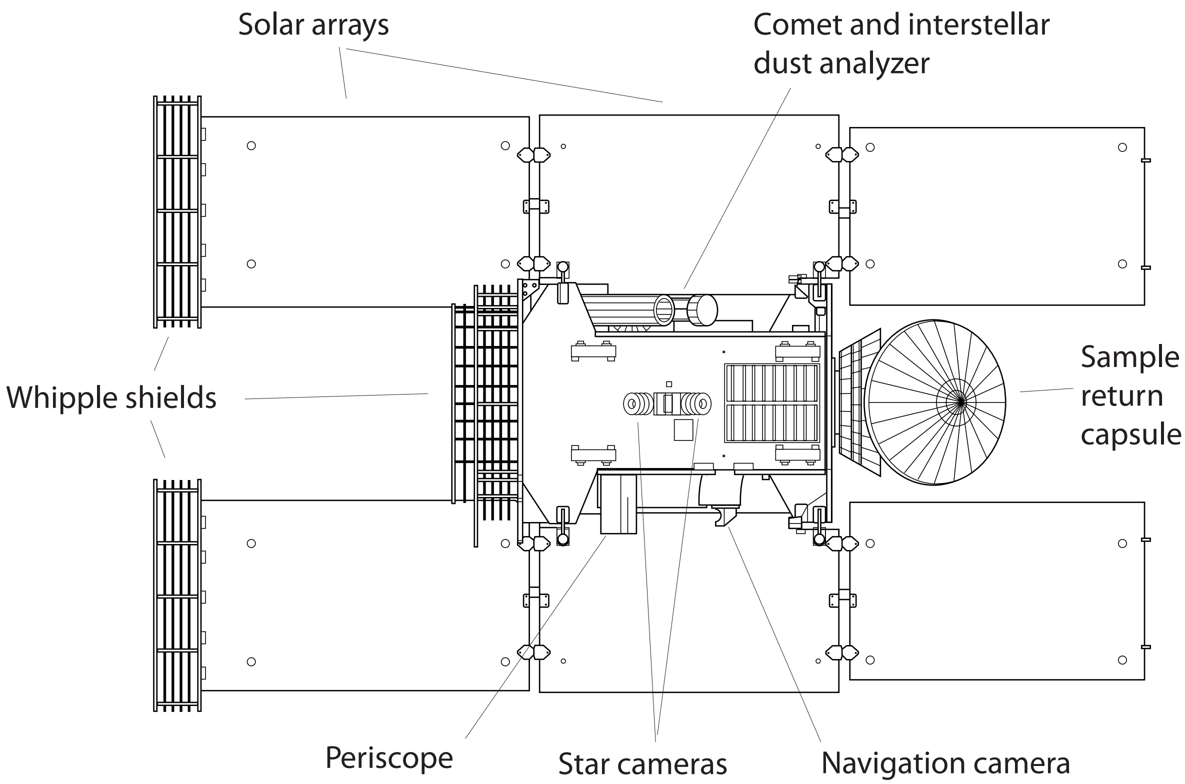
Aerogel Dust Collectors

To collect particles without damaging them, Stardust used an extraordinary substance called aerogel -- a silicon-based solid with a porous, sponge-like structure in which 99 percent of the volume is empty space. Originally invented in 1931 by a researcher at the College of the Pacific in Northern California, aerogel is made from a gelatin-like mix of silica and a liquid. The mixture is set in molds of the desired shape and thickness, and then pressure-cooked at high temperature to remove the liquid.

Over the past several years, aerogel has been made and flight-qualified at the Jet Propulsion Laboratory for space missions. A cube of aerogel looks like solid, pale-blue smoke. It is the lightest-weight, lowest-mass solid known, and has been found to be ideal for capturing tiny particles in space. There is extensive experience, both in laboratory and space flight experiments, in using aerogel to collect hypervelocity particles. Eight space shuttle flights have been equipped with aerogel collectors.

The exotic material has many unusual properties, such as uniquely low thermal and sound conductivity, in addition to its exceptional ability to capture hypervelocity dust. Aerogel was also used as a lightweight thermal insulator on Mars Pathfinder’s Sojourner rover. When Stardust flew through the comet’s coma, the impact velocity of particles as they are captured were up to six times the speed of a bullet fired from a high-powered rifle.
Although the particles captured in aerogel are each smaller than a grain of sand, high-





Stardust spacecraft

speed capture in most substances would alter their shape and chemical composition -- or vaporize them entirely. With aerogel, however, particles are softly caught in the material and slowed to a stop. When a particle hits the aerogel, it buries itself, creating a carrot-shaped track in the aerogel up to 200 times its own length as it slows down and comes to a stop. The aerogel made for the Stardust mission has extraordinary, water-like clarity that will allow scientists to locate a particle at the end of each track etched in the substance. Each narrow, hollow cone leading to a particle will easily be seen in the aerogel with a stereo microscope.

The sizes of the particles collected in the aerogel are expected to range mostly from less than a micron (a millionth of a meter, or 1/25,000th of an inch, or about 1/100th of the width of a human hair) to nearly a millimeter). Most of the scientific analysis will be devoted to particles that are 15 microns (about 1/1,700th of an inch, or about one-third the width of a human hair) in size. The Stardust science team expects that the samples returned will be profoundly complex, and some particles will be probed for years in research labs.

One side of the dust collection module, called the “A side”, was used for the comet encounter, while the opposite side (“B side”) has been used for interstellar collection. More than 1,000 square centimeters (160 square inches) of collection area is provided on each side. Each of Stardust’s two collectors has 130 rectangular blocks of aerogel each measuring 2 by 4 centimeters (0.8 by 1.6 inches), plus two slightly smaller rhomboidal blocks.

The thickness of the aerogel on the cometary particle collection side is 3 centimeters (1.2 inches), while the thickness of the aerogel on the interstellar dust particle collection side is 1 centimeter (0.4 inch). The density of the aerogel is graded -- less dense at the point of particle entry, and progressively denser deeper in the material. Each block of aerogel is held in a frame with thin aluminum sheeting.

Overall, the collection unit resembles a metal ice cube tray set in an oversize tennis racket. It is similar to previous systems used to collect particles in Earth orbit on SpaceHab and other space shuttle-borne experiments. The sample return capsule is a little less than a meter (or yard) in diameter, and opens like a clamshell to extend the dust collector into the dust stream. After collecting samples, the cell assembly folds down for stowage into the sample return capsule.

Comet and Interstellar Dust Analyzer

The comet and interstellar dust analyzer is derived from the design of an instrument that flew on the European Space Agency’s Giotto spacecraft and the Soviet Union’s Vega spacecraft when they encountered Comet Halley in 1986. The instrument obtained unique data on the chemical composition of individual particulates in Halley’s coma. Stardust’s version of the instrument studied the chemical composition of particulates in the coma of comet Wild 2.

The instrument is what scientists call a “time-of-flight” mass spectrometer, which separates the masses of ions by comparing differences in their flight times. When a dust particle hits the instrument’s target, the impact creates ions which are extracted from the particle by an electrostatic grid. Depending on the polarity of the target, positive or negative ions can be extracted. As extracted ions move through the instrument, they are reflected and then detected. Heavier ions take more time to travel through the instrument than lighter ones, so the flight times of the ions are then used to calculate their masses. From this information, the ion’s chemical identification can be made. In all, the instrument consists of a particle inlet, a target, an ion extractor, a mass spectrometer and an ion detector.

Co-investigator in charge of the comet and interstellar dust analyzer is Dr. Jochen Kissel of the Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany. The instrument was developed and fabricated by von Hoerner & Sulger GmbH, Schwetzingen, Germany, under contract to the German Space Agency and the Max-Planck-Institut. Software for the instrument was developed by the Finnish Meteorological Institute, Helsinki, Finland, under subcontract to von Hoerner & Sulger.

Dust Flux Monitor

The dust flux monitor measures the size and frequency of dust particles in the comet’s coma. The instrument consists of two film sensors and two vibration sensors. The film material responds to particle impacts by generating a small electrical signal when penetrated by dust particles. The mass of the particle is determined by measuring the size of the electrical signals. The number of particles is determined by counting the number of signals. By using two film sensors with different diameters and thicknesses, the instrument provides data on what particle sizes were encountered and what the size distribution of the particles is.

The two vibration sensors are designed to provide similar data for larger particles, and are installed on the Whipple shield that protect the spacecraft’s main bus. These sensors detected the impact of large comet dust particles that penetrate the outer layers of the shield. This system, essentially a particle impact counter, will give mission engineers information about the potential dust hazard as the spacecraft flies through the coma environment. Co-investigator in charge of the dust flux monitor is Dr. Anthony Tuzzolino of the University of Chicago, where the monitor was developed.

Navigation Camera

Stardust’s navigation camera is an amalgam of flight-ready hardware left over from other NASA solar system exploration missions. The main camera is a spare wide-angle unit left over from the two Voyager spacecraft missions launched to the outer planets in 1977. The camera uses a single clear filter, thermal housing, and spare optics and mechanisms. For Stardust, designers added a thermal radiator.

Also combined with the camera is a modernized sensor head left over from the Galileo mission to Jupiter launched in 1989. The sensor head uses the existing Galileo design updated with a 1024-by-1024-pixel array charge-coupled device (CCD) from the Cassini mission to Saturn, but has been modified to use new miniature electronics. Other components originated for NASA's Deep Space 1 program.

During distant imaging of the comet's coma, the camera took pictures through a periscope in order to protect the camera's primary optics as the spacecraft enters the coma. In the periscope, light is reflected off mirrors made of highly polished metals designed to minimize image degradation while withstanding particle impacts. During close approach, the nucleus was tracked and 72 images were taken.

Propulsion System

The Stardust spacecraft needs only a relatively modest propulsion system because of its carefully designed trajectory, which included three loops around the Sun with flybys of Earth, the comet and an asteroid plus its return to Earth.

The spacecraft is equipped with two sets of thrusters that use hydrazine as a monopropellant. Eight larger thrusters, each of which puts out 4.4 newtons (1 pound) of thrust, will be used for trajectory correction maneuvers or turning the spacecraft. Eight smaller thrusters producing 0.9 newton (0.2 pound) of thrust each are used to control the spacecraft's attitude, or orientation. The thrusters are in four clusters located on the opposite side of the spacecraft from the deployed aerogel. At launch the spacecraft carried 85 kilograms (187 pounds) of hydrazine propellant.

Attitude Control

The attitude control system manages the spacecraft's orientation in space. Like most solar system exploration spacecraft, Stardust is three-axis stabilized, meaning that its orientation is held fixed in relation to space, as opposed to spacecraft that stabilize themselves by spinning.

Stardust determines its orientation at any given time using a star camera or one of two inertial measurement units, each of which consists of three ring-laser gyroscopes and three accelerometers. The spacecraft's orientation is changed by firing thrusters. The inertial measurement units are needed only during trajectory correction maneuvers and during the fly-through of the cometary coma when stars may be difficult to detect. Otherwise, the vehicle can be operated in a mode using only stellar guidance for spacecraft positioning. Two Sun sensors serve as backup units, coming into play if needed to augment or replace the information provided by the rest of the attitude control system's elements.

Command and Data Handling

The spacecraft's computer is embedded in the spacecraft's command and data-handling subsystem, and provides computing capability for all spacecraft subsystems. At its heart is a RAD6000 processor, a radiation-hardened version of the PowerPC chip used on some models of Macintosh computers. It can be switched between clock speeds of 5, 10 or 20 MHz. The computer includes 128 megabytes of random-access memory (RAM); unlike many previous spacecraft, Stardust does not have an onboard tape recorder, but instead stores data in its RAM for transmission to Earth. The computer also has 3 megabytes of programmable memory that can store data even when the computer is powered off.

The spacecraft uses about 20 percent of the 128 megabytes of data storage for its own internal housekeeping. The rest of the memory is used to store science data and for computer programs that control science observations. Memory allocated to specific instruments includes about 75 megabytes for images taken by the navigation camera, 13 megabytes for data from the comet and interstellar dust analyzer, and 2 megabytes for data from the dust flux monitor.

Power

Two solar array panels affixed to the spacecraft were deployed shortly after launch. Together they provide 6.6 square meters (7.9 square yards) of solar collecting area using high-efficiency silicon solar cells. One 16-amp-hour nickel-hydrogen battery provides power when the solar arrays are pointed away from the Sun and during peak power operations.

Thermal Control

Stardust's thermal control subsystem uses louvers to control the temperature of the inertial measurement units and the telecommunications system's solid-state power amplifiers. Thermal coatings and multi-layer insulation blankets and heaters are used to control the temperature of other parts of the spacecraft.

Telecommunications

Stardust is equipped with a transponder (radio transmitter/receiver) originally developed for the Cassini mission to Saturn, as well as a 15-watt radio frequency solid-state amplifier. Data rates will range from 40 to 33,000 bits per second.

During cruise, communications are mainly conducted through the spacecraft's medium-gain antenna. Three low-gain antennas are used for initial communications near Earth and to receive commands when the spacecraft is in nearly any orientation.

A 0.6-meter-diameter (2-foot) high-gain dish antenna is used primarily for communication immediately following closest approach to the comet. Stardust will use it to transmit images of the comet nucleus, as well as data from the comet and interstellar dust analyzer and the dust flux monitor, at a high data rate to minimize the transmission time and the risk of losing data during the extended time that would be required to transmit the data through the medium-gain antenna. Most data from the spacecraft will be received through the Deep Space Network's 34-meter-diameter (112-foot) ground antennas, but 70-meter (230-foot) antennas will be used during some critical telecommunications phases, such as when Stardust transmits science data during and after the comet encounter.

Redundancy

Virtually all spacecraft components are redundant, with critical items "cross-strapped" or interconnected so that they can be switched in or out most efficiently. The battery includes an extra pair of cells. Fault protection software is designed so that the spacecraft is protected from reasonable, credible faults without unnecessarily putting the spacecraft into a safe mode due to unanticipated but probably benign glitches.

Whipple Shields

The shields that protected Stardust from the blast of cometary particles is named for American astronomer Dr. Fred L. Whipple, who in 1950 developed the "dirty snowball" model of the cometary nucleus as a mixture of dark organic material, rocky grains and water ice. Whipple also came up with the idea of shielding spacecraft from high-speed collisions of the bits and pieces that are ejected from comets and asteroids as they circle the Sun.

The system includes two bumpers at the front of the spacecraft -- which protect the solar panels -- and another shield protecting the main spacecraft body. Each of the shields is built around composite panels designed to disperse particles as they impact, augmented by blankets of a ceramic cloth called Nextel that further dissipate and spread particle debris. The Whipple shield was designed to protect Stardust from impacts of comet rocks as large as 1 centimeter (about 0.4 inch).

Sample Return Capsule

The sample return capsule is a blunt-nosed cone with a diameter of 81 centimeters (32 inches). It has five major components: a heat shield, back shell, sample canister, parachute system and avionics. The total mass of the capsule, including the parachute system, is 45.7 kilograms (101 pounds).

A hinged clamshell mechanism opens and closes the capsule. The dust collector fits inside, extending on hinges to collect samples and retracting to fold down back inside the capsule. The capsule is encased in ablative materials to protect the samples stowed in its interior from the heat of reentry.

The return capsule is made of a graphite-epoxy composite covered with a thermal protection system. The Earth-facing edge of the thermal protection system is made of a phenolic-impregnated carbon ablator developed by NASA's Ames Research Center for use on high-speed reentry vehicles. The capsule's heat shield will remain attached to the capsule throughout descent and serves as a protective cover for the sample canister at touchdown.

The back-shell structure is covered with a thermal protection system that is made of a cork-based material called SLA 561V. The material was developed by Lockheed Martin for use on the Viking missions to Mars in the 1970s, and has been used on several space missions including NASA's Mars Pathfinder, Genesis and Mars Exploration Rover missions. The back shell's structure provides the attach points for the parachute system.

The sample canister is an aluminum enclosure that holds the aerogel and the mechanism used to deploy and stow the aerogel collector during the mission. The canister is mounted on a composite equipment deck suspended between the back shell and heat shield. The parachute system incorporates a drogue and main parachute inside a single canister.

As the capsule descends toward Earth, a gravity-switch sensor and timer will trigger a pyrotechnic gas cartridge that will pressurize a mortar tube and expel the drogue chute. The drogue chute will be deployed to provide stability to the capsule when it is at an altitude of approximately 30 kilometers (100,000 feet) moving at a speed of about mach 1.4. Based on information from timer and backup pressure transducers, a small pyrotechnic device will release the drogue chute from the capsule at an altitude of approximately 3 kilometers (10,000 feet). As the drogue chute pulls away, it will extract the 8.2-meter-diameter (27-foot) main chute from the canister. Upon touchdown, a cutter will fire to cut the main chute riser so that winds do not drag the capsule across the terrain.

The capsule carries a UHF radio locator beacon to be used in conjunction with locator equipment on the recovery helicopters. The beacon will be turned on at main parachute deployment and will remain on until turned off by recovery personnel. The beacon is powered by redundant sets of lithium sulfur dioxide batteries, which have long shelf life and tolerance to wide temperature extremes, and are safe to handle. The capsule carries sufficient battery capacity to operate the UHF beacon for at least 20 hours.

Science Objectives

The purpose of the Stardust mission is to expand the knowledge of comets by flying a spacecraft through the coma of Comet Wild 2, collecting samples from the comet, and returning those samples to Earth for laboratory analysis. Additional objectives include collecting and returning interstellar particles, imaging the comet nucleus, and in situ analysis of comet particles.

The mission's primary goal was to collect samples of a comet's coma and return them to Earth. In addition, interstellar dust samples were also gathered en route to the comet.

Laboratory investigation of the returned samples using instruments such as electron microscopes, ion microprobes, atomic force microscopes, synchrotron microprobes and laser probe mass spectrometers will allow examination of cometary matter and interstellar grains at the highest possible level of detail. Advances in microanalytical instruments provide unprecedented capabilities for analysis on the micron and submicron level, even to the atomic scale for imaging.

These instruments will provide direct information on the nature of the actual particles that initiated the formation of the Sun and planets 4.6 billion years ago. They will provide a highly intimate view of both pre-solar dust and solar nebula materials that existed at the very edge of the solar system at the time of its formation. Such materials will be compared with primitive meteorites and interplanetary dust samples to understand how solids that built the solar system were formed. One of the most important aspects of the mission is that it will provide materials from the edge of the solar system to be compared with primitive materials that formed in the inner solar system and are preserved in meteorites from the asteroid belt. The ability to compare the ancient asteroidal materials that formed just beyond the orbit of Mars with the cometary solids that accreted near Pluto will provide fundamental insight into the materials, processes and environments that existed during the origin and early evolution of the solar system.

The Stardust mission is also expected to return interstellar grains formed around other stars. These will include both grains that assimilated into comets during their formation as well as dust from the galaxy that is currently passing the Sun. Interstellar grains are generally studied by astronomical techniques capable only of revealing general physical properties such as size and shape. The recent discovery and study of rare interstellar grains preserved in meteorites and interplanetary dust has shown that they contain excellent records about the nature of their parent stars, including details of the complex nuclear reactions that occur within the stars. Most of the interstellar grains that have been identified in meteorites are grains that formed in gas flows from carbon-rich stars such as red giants and what are called AGB stars. It is expected Stardust will collect grains produced by star types that are major sources of interstellar dust.

Comets are now known to contain large quantities of volatiles, including organic compounds, as well as a rich variety of microparticles of various types (pure organic particles, silicates, sulfides and mixed particles) with sizes ranging as low as submicron diameters. Organic particulates actually consist of several sub-populations, which can be described based on the elements that they are made up of. These include particles containing:

- Hydrogen, carbon and nitrogen
- Hydrogen, carbon and oxygen
- Hydrogen and carbon
- Hydrogen, carbon, nitrogen and oxygen, with and without magnesium (termed “CHON” particles)

Since comets are rich in water and other volatiles, it has been postulated that they carried to Earth elements critical to the origin of life. The study of cometary material is essential for understanding the formation of the solar system and the role of organic matter from interstellar sources. Astronomers have identified some 60 compounds in interstellar clouds, three-fourths of which are organic. (“Organic” means that the compound is carbon-based, but not necessarily biological in origin.) There is compelling evidence that four of the first five interstellar molecules detected by astronomers are present in comets, and the fifth might be also.

Stardust Science Team

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The volatiles and silicates that appear to be in comets also are found in interstellar clouds. How the elements necessary for life entered the solar system, were transformed by solar system processes, were distributed among planetary bodies, and what molecular and mineral forms they took during this history are questions of major importance for astrobiology. Comparing the composition of the volatiles from cometary material with those found in carbonaceous meteorites and interplanetary dust will provide a basis to determine which particles, if any, have common source regions.

Finally, the discovery of an iridium-rich layer in rocks at Earth's Cretaceous-Tertiary geologic boundary marking the end of the age of the dinosaurs about 65 million years ago has, along with other evidence, shown that that impact of an asteroid-sized body with Earth was probably responsible for the demise of the giant creatures and the death of many of Earth's creatures living at the time. Although the chance of finding a unique elemental signature in captured cometary coma material might be slight, such a discovery would be enormously valuable in distinguishing whether it was an asteroid or a comet that made the impact.

Why Stardust?

Beyond the orbits of the planets on the outer fringes of the solar system, a vast swarm of perhaps a trillion dormant comets circles the Sun. Frozen bodies of dust and ice, they are the most distant survivors of the disc of gas and dust that formed the Sun and planets about 4.6 billion years ago. From time to time, the gravitational pulls of other bodies will nudge some of them out of their orbits, plunging them into the inner solar system, where they erupt with glowing tails as they loop around the Sun.

Closer to home, a stream of interstellar dust flows continuously through the solar system. Each about 1 percent the width of a human hair, these tiny particles formed around ancient stars, are the initial building blocks of planetary systems like our own. This “stardust” is literally the stuff of which we are all made, being the source of nearly all of the elements on Earth heavier than helium.

These two niches bearing clues of the dawn of the solar system are the target for NASA’s Stardust mission. The spacecraft used a collector mechanism that employed a unique substance called aerogel to snag comet particles as well as interstellar dust flowing through the solar system, returning them to Earth for detailed study in laboratories.

Data returned from the Stardust spacecraft and the precious samples it returns to Earth will provide opportunities for significant breakthroughs in areas of key interest to astrophysics, planetary science and astrobiology. The samples will provide scientists with direct information on the solid particles that permeate our galaxy.

Stardust’s cometary dust and interstellar dust samples will help provide answers to fundamental questions about the origin of solar systems, planets and life: How did the elements that led to life enter the solar system? How were these materials transformed within the solar system by forces such as heating and exposure to ultraviolet light? How were they distributed among planetary bodies, and in what molecular and mineral-based forms? These questions are of major importance for astrobiology and the search for life-generating processes and environments elsewhere in the universe.

Comets

Though frequently beautiful, comets traditionally have stricken terror as often as they have generated excitement as they wheel across the sky during their passage around the Sun. Astrologers interpreted the sudden appearances of the glowing visitors as ill omens presaging famine, flood or the death of kings. Even as recently as the 1910 appearance of Halley’s Comet, entrepreneurs did a brisk business selling gas masks to people who feared Earth’s passage through the comet’s tail.

In the 4th century B.C., the Greek philosopher Aristotle concluded that comets were some kind of emission from Earth that rose into the sky. The heavens, he maintained, were perfect and orderly; a phenomenon as unexpected and erratic as a comet surely could not be part of the celestial vault. In 1577, Danish astronomer Tycho Brahe carefully examined the positions of a comet and the Moon against the stars during the evening and predawn morning. Due to parallax, a close object will appear to change its position against the stars more than a distant object will, similar to holding up a finger and looking at it while closing one eye and then the other. The Moon appeared to move more against the stars from evening to morning than the comet did, leading Tycho to conclude that the comet was at least four times farther away.

A hundred years later, the English physicist Isaac Newton established that a comet appearing in 1680 followed a nearly parabolic orbit. The English astronomer Edmund Halley used Newton's method to study the orbits of two dozen documented cometary visits. Three comet passages in 1531, 1607 and 1682 were so similar that he concluded they in fact were appearances of a single comet wheeling around the Sun in a closed ellipse every 75 years. He successfully predicted another visit in 1758-9, and the comet thereafter bore his name.

Since then, astronomers have concluded that some comets return relatively frequently, in intervals ranging from 3 to 200 years; these are the so-called "short-period" comets. Others have enormous orbits that bring them back only once in many centuries.

In the mid-1800s, scientists also began to turn their attention to the question of comets' composition. Astronomers noted that several major meteor showers took place when Earth passed through the known orbits of comets, leading them to conclude that the objects are clumps of dust or sand. By the early 20th century, astronomers studied comets using the technique of spectroscopy, breaking down the color spectrum of light given off by an object to reveal the chemical makeup of the object. They concluded that comets also emitted gases as well as molecular ions.

In 1950, the American astronomer Fred L. Whipple authored a major paper proposing the "dirty snowball" model of the cometary nucleus. This model, which has since been widely adopted, pictures the nucleus as a mixture of dark organic material, rocky grains and water ice. ("Organic" means that the compound is carbon-based, but not necessarily biological in origin.) Typical active comets are a few kilometers across. The shields that protected the Stardust spacecraft from the impacts of centimeter-sized rocks were named for Whipple because he conceived this technology half a century ago, just before the dawn of the space age.

Comets contain icy material, proving that they formed in the colder regions of the solar nebula. In 1950, the Dutch astronomer Jan Hendrick Oort (1900-1992) used indirect reasoning from observations to establish the existence of a vast cloud of comets orbiting many billions of miles from the Sun -- perhaps 50,000 astronomical units (AU) away (one AU is the distance from Earth to the Sun), or nearly halfway to the nearest star. This region has since become known as the Oort Cloud.

Other Comet Missions

Comets have been studied by several spacecraft, not all of which were originally designed for that purpose. Several new missions to comets are being developed for launch in coming years.

Other past and present cometary missions include:

❑ In 1985, NASA modified the orbit of the International Sun-Earth Explorer spacecraft to execute a flyby of Comet 21P/Giacobini-Zinner. At that point, the spacecraft was renamed **International Comet Explorer**. It successfully flew through the tail of comet Giacobini-Zinner in 1985 and flew in the vicinity of comet 1P/Halley in 1986.

❑ An international armada of robotic spacecraft flew out to greet Halley's Comet during its return in 1986. The fleet included the European Space Agency's **Giotto**, the Soviet Union's **Vega 1** and **Vega 2**, and Japan's **Sakigake** and **Suisei** spacecraft.

❑ Comet Shoemaker-Levy 9's spectacular collision with Jupiter in 1994 was observed by NASA's **Hubble Space Telescope**, the Jupiter-bound **Galileo** spacecraft and the Sun-orbiting **Ulysses** spacecraft.

❑ **Deep Space 1** launched from Cape Canaveral on October 24, 1998. During a highly successful primary mission, it tested 12 advanced, high-risk technologies in space. In an extremely successful extended mission, it encountered comet 19P/Borrelly and returned the best images and other scientific data taken from a comet up to that time.

❑ The **Comet Nucleus Tour**, or Contour, mission launched from Cape Canaveral on July 3, 2002. Six weeks later, on August 15, contact with the spacecraft was lost after a planned maneuver that was intended to propel it out of Earth orbit and into its comet-chasing solar orbit.

❑ A European Space Agency mission, **Rosetta**, was launched March 2, 2004 to orbit comet 67P/Churyumov-Gerasimenko and deliver a scientific package to its surface via a lander in 2014. NASA provided scientific instruments for the cometary orbiter.

❑ Launched in January 2005, NASA's **Deep Impact** spacecraft traveled about 431 million kilometers (268 million miles) to the vicinity of comet Tempel 1. On July 3, 2005, the spacecraft deployed an impactor that was essentially "run over" by the nucleus of comet Tempel 1 on July 4. Before, during and after the demise of this 372-kilogram (820-pound) impactor, a flyby spacecraft watched the 6.5-kilometer (about 4-mile) wide comet nucleus from nearby, collecting pictures and data of the event.

A year later, the Dutch-born American astronomer Gerard Kuiper (1905-1973) made the point that the Oort Cloud is too distant to act as the nursery for short-period comets. He suggested the existence of bodies lying just outside the orbits of the planets at perhaps 30 to 100 AU from the Sun; this has become generally known as the Kuiper Belt. Gravitational tugs from the outer planets occasionally perturb these bodies into orbits that ultimately reach inside the orbit of Jupiter where solar heating begins to release volatile materials. These comets are scattered inwards from planet to planet like a game of cosmic billiards.

The Oort Cloud, by contrast, would be the source of long-period comets. They are periodically nudged from their orbits by any one of several influences -- perhaps the gravitational pull of a passing star or giant molecular cloud, or tidal forces of the Milky Way Galaxy. It is generally believed that the Oort cloud comets actually formed closer to the Sun than the Kuiper belt comets and were ejected outwards by close encounters with giant planets. When the solar system was forming, small, icy, comet-like bodies were the dominant form of solid planetary building block. The Oort Cloud and the Kuiper Belt are two places where a tiny fraction of the original ice-rich bodies have survived over the full history of the solar system. All of the others either collided with planets or the Sun or were ejected into the galaxy.

In addition to the length of time between their visits, another feature that distinguishes short- and long-period comet is that the orbits of short-period comets are all fairly close to the ecliptic plane, the plane in which Earth and most other planets orbit the Sun. Long-period comets, by contrast, dive inwards toward the Sun from virtually any part of the sky; many of them have retrograde orbits, orbiting in the opposite direction to that of the planets. The Kuiper Belt is a relatively flat ring in the outer part of the solar system, whereas the Oort Cloud is a three-dimensional sphere surrounding the solar system.

Residing at the farthest reaches of the solar system, comets were not strongly influenced by most of the processes that modified small bodies that formed closer to the Sun. As the preserved building blocks of the outer solar system, comets offer direct clues to the materials and processes that formed the planets 4.6 billion years ago.

The geologic record of the Moon shows that, about 3.9 billion years ago, a period of heavy comet or asteroid bombardment tapered off. The earliest evidence of life on Earth dates from just after the end of this heavy bombardment. Before this time, Earth was impacted with objects from the outer solar system that were large enough to heat Earth's surface to sterilizing temperatures. Scientists therefore wonder: How could life form so quickly when the period of heavy bombardment ended? Part of the answer may be that comets, which are abundant in both water and carbon-based molecules, delivered essential ingredients for life to begin.

Comets are also at least partially responsible for the delivery of Earth's water. While

Earth has long been regarded as the "water planet," it and the other terrestrial planets (Mercury, Venus and Mars) are actually poor in the percentage of water and in carbon-based molecules they contain when compared to objects that reside in the outer solar system at Jupiter's orbit or beyond. Comets may contain up to 50 percent water by weight and about 10 to 20 percent carbon by weight. It has long been suspected that what little carbon and water there is on Earth was delivered here by objects such as comets and asteroids that came from in colder regions of the solar nebula where it was possible to incorporate water into solid bodies.

While comets are a likely source for life's building blocks, they have also played a devastating role in altering life on our planet. A comet or asteroid is credited as the likely source of the impact that changed Earth's climate, wiped out the dinosaurs and gave rise to the age of mammals 65 million years ago. A catastrophic collision between a comet or asteroid and Earth of several kilometers in size is estimated to happen at intervals of several tens of millions of years.

Right Place, Right Time, Right Snowball

Comet 81P/Wild 2 is a periodic comet that currently moves about the Sun in an elliptic orbit every 6.39 years. Its nucleus is thought to be a mix of ice and dust, with dimensions of 3.3 by 4 by 5.5 kilometers (2 by 2.5 by 3.4 miles).

Until September 10, 1974, comet Wild 2's orbit lay between Jupiter and a point past Uranus. But on that date over 30 years ago, the comet passed within 897,500 kilometers (557,735 miles) of the solar system's biggest planet, Jupiter. That encounter with Jupiter altered the comet's orbit, carrying it into the inner solar system. The new flight path brings it as close to the Sun as just beyond the distance of Mars and far from the Sun as about Jupiter. On January 6, 1978, astronomer Paul Wild (pronounced "Vilt") discovered the comet during its first passage relatively near to the Earth -- passing within 181,014,000 kilometers (112,476,679 miles).

When a comet comes close enough to the Sun, solar heating causes it to lose volatile material through a process called sublimation. This happens when a solid turns to vapor without first melting into a liquid. If a comet lasts long enough, after about 1,000 orbits inside the orbit of Jupiter, it can lose most of its volatile materials and no longer generate a coma or tail. Many comets mysteriously break up into fragments long before they lose all their volatiles and literally run out to steam.

When Stardust reached Wild 2 , the comet had made only five trips around the Sun in its new orbit. By contrast, Comet Halley has passed close to the Sun more than 100 times, coming close enough to have been greatly altered from its original condition. The past history of Wild 2 is unknown but it is likely that it had previously been inside the orbit of Jupiter. Scientists believe the comet probably formed near the orbit of Pluto where it orbited for nearly the entire age of the solar system. In the last few million years, it began a "wandering stage" where repeated gravitational tugs from plan-

NASA's Discovery Program

Stardust is a mission under NASA's Discovery Program, which sponsors frequent, cost-capped solar system exploration missions with highly focused scientific goals. Created in 1992, the Discovery Program competitively selects proposals submitted by teams led by scientists, supported by organizations that manage the project, as well as partners that build and fly the spacecraft. In recent years, NASA has identified several finalists from dozens of mission proposals submitted. These finalists receive funding to conduct feasibility studies for an additional period of time before a final selection is made.

Other missions in the Discovery Program are:

❑ The **Near Earth Asteroid Rendezvous** spacecraft (later renamed Near Shoemaker) was launched Feb. 17, 1996 and became the first spacecraft to orbit an asteroid when it reached Eros in February 2000. A year later, it became the first spacecraft to land on an asteroid when it put down on Eros, providing the highest resolution images ever obtained of an asteroid, showing features as small as one centimeter across. The mission was managed by Johns Hopkins University's Applied Physics Laboratory.

❑ **Mars Pathfinder** was launched Dec. 4, 1996 and landed on Mars on July 4, 1997, demonstrating a unique way of touching down with airbags to deliver a small robotic rover. Mars Pathfinder was managed by NASA's Jet Propulsion Laboratory.

❑ Launched Jan. 7, 1998, **Lunar Prospector** entered orbit around Earth's Moon five days later, circling at an altitude of about 100 kilometers (60 miles). The principal investigator was Dr. Alan Binder of the Lunar Research Institute, Gilroy, Calif., with project management by NASA's Ames Research Center.

❑ Launched Aug. 8, 2001, **Genesis** collected pristine samples of solar wind beyond the Moon's orbit. The Genesis sample return capsule entered Earth's atmosphere over the Utah Test & Training Range on Sept. 8, 2004, but its parachute system did not deploy. The mission's samples of solar wind were recovered and are currently being analyzed by scientists at NASA's Johnson Space Center. Genesis was managed by the Jet Propulsion Laboratory, with Dr. Donald Burnett of the California Institute of Technology as principal investigator.

❑ The **Comet Nucleus Tour** or Contour, launched from Cape Canaveral on July 3, 2002. Unfortunately, six weeks later, on Aug. 15, contact with the spacecraft was lost after a planned maneuver that was intended to propel it out of Earth orbit and into its comet-chasing solar orbit. Contour was managed by Johns Hopkins University's Applied Physics Laboratory, and the principal investigator was Dr. Joseph Veverka of Cornell University.

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❑ The **Mercury Surface, Space Environment, Geochemistry and Ranging** (Messenger) mission was launched Aug. 3, 2004. Entering orbit around the planet closest to the Sun in September 2009, the spacecraft will produce a global map and details about Mercury's surface, interior, atmosphere and magnetosphere. The mission is managed by Johns Hopkins University's Applied Physics Laboratory, and the principal investigator is Dr. Sean C. Solomon of the Carnegie Institution.

❑ Launched in January 2005, NASA's **Deep Impact** spacecraft traveled about 431 million kilometers (268 million miles) to the vicinity of comet Tempel 1. On July 3, 2005, the spacecraft deployed an impactor that struck the comet nucleus as a flyby spacecraft recorded observations. The mission was managed by NASA's Jet Propulsion Laboratory, and the principal investigator was Dr. Michael A'Hearn of the University of Maryland, College Park, Md.

❑ The **Dawn** mission will undertake a journey in both space and time by traveling to two of the oldest and most massive asteroids in our solar system, Vesta and Ceres. Planned for launch in May 2006, the ion-propulsion-powered spacecraft will reach Vesta in 2010 and Ceres in 2014. These minor planets have existed since the earliest time of solar system formation. Dawn is managed by NASA's Jet Propulsion Laboratory, and Dr. Christopher Russell of UCLA is the principal investigator.

❑ The **Kepler** mission is designed to find Earth-size planets in orbit around stars like our Sun outside of the solar system. It will survey our galactic neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the "habitable zone," defined by scientists as the distance from a star where liquid water can exist on a planet's surface. Planned for launch in fall 2007, Kepler will monitor 100,000 stars similar to our Sun for four years. Dr. William Borucki of NASA's Ames Research Center is the principal investigator, with project management by NASA's Jet Propulsion Laboratory.

ets started it on a series of encounters that led it to its present orbit inside the orbit of Jupiter. If it survives the effects of solar heating and also does not fragment, Wild 2 will most likely be ejected from the solar system or perhaps collide with a planet within the next few million years.

Interstellar Dust

In 1990, NASA launched the Ulysses spacecraft on a flight path that would take it close to Jupiter, in turn flinging it into an orbit around the Sun far above and below the ecliptic, the plane in which most planets orbit the Sun. While en route from Earth to Jupiter, the spacecraft's dust detector measured a flow of dust particles -- each about a micron in size, or 1 percent of the diameter of a human hair -- entering the solar system from interstellar space. This observation was corroborated by a similar dust detector on the Galileo spacecraft, which reached Jupiter in 1995.

Interstellar dust is ubiquitous in the space between the stars of the Milky Way Galaxy. The dust curtains huge areas of the sky; the broad, dark line across the length of the Milky Way that can be seen with the naked eye is a blanket of interstellar dust. The numerous but tiny particles carry nearly all of the atoms heavier than helium that are used to make new generations of stars, planets and even life. All of the atoms in our bodies were inside these grains before the Sun and planets formed.

As the Sun orbits the galactic center, it cuts through the dust like a car driving through rain. From our perspective within the solar system, the dust seems to be flowing from approximately the direction that the Sun is moving toward -- a point called the “solar apex” in the constellation Hercules.

Interstellar dust provided the initial building blocks for making Earth and the other solid bodies in the solar system. In the life cycle of stars, elements coalesce under gravity to form the star, which in develops internal temperatures high enough to drive ongoing nuclear reactions. All elements heavier than helium were made inside stars by these nuclear reactions. When stars reach the ends of their lives they eject some of these elements back into space where they condense into tiny grains of interstellar dust. The resulting interstellar particles contain a record of the processes at work in their parent stars as well as the environments they have passed through in the galaxy. This information is retained in particles at a scale smaller than a micron.

Interstellar dust forms by condensation in circumstellar regions around evolved stars of different types, including red giants, carbon stars, novas and supernovas. The process gives rise to silicate grains when there is more oxygen than carbon in the star, and carbon-based grains when the carbon content exceeds that of oxygen. Pristine grains will retain the isotopic signatures of the environments they formed in.

In the past decade, scientists have gained new understanding about the formation and early evolution of the solar system and the role of interstellar dust and comets in that process. Studies of interstellar dust have been conducted with Earth and space-based telescopes; in addition, scientists have positively identified interstellar grains that are contained inside certain meteorites and ultra-primitive interplanetary dust collected with U-2 aircraft in the stratosphere. The samples returned by Stardust will be compared with these and others to better understand how dust evolves from its interstellar state to help create stars, planets and life in the universe.

Infrared observations have also provided new knowledge of star-formation and the role that dust plays in that process. Scientists have found both similarities and differences between interstellar dust and cometary composition. The same gases, ice particles and silicates believed to be in comets also are found in interstellar clouds.

Even though the interstellar dust particles are small, they contain billions of atoms and open a significant new window of information on galactic and nebular processes, materials and environments. Having actual samples in hand provides many unique advantages. Just as the return of lunar samples by the Apollo missions of the 1960s and 1970s revolutionized our understanding of the Moon, scientists expect that the Stardust mission's sample return will also have a profound impact on our knowledge of comets and stars.

Earth Assist

Assisting the Stardust team in their celestial pursuit of comet Wild 2 are several teams of Earth-based astronomers. These observatories made observations and measurements of Wild 2 from mid to late December 2003. These observations assisted the Stardust team in validating the size of coma and amount of activity taking place on comet Wild 2, as well as assisting in further reducing uncertainty in the plotting of the comet's orbit.

Program/Policy Management

Stardust's principal investigator is Dr. Donald Brownlee of the University of Washington, Seattle. Dr. Peter Tsou of NASA's Jet Propulsion Laboratory, Pasadena, Calif., is deputy principal investigator.

The Stardust mission is managed by the Jet Propulsion Laboratory for NASA's Science Mission Directorate, Washington. At NASA Headquarters, Mary Cleave is associate administrator for space science. Andy Dantzler is the director of NASA's Solar System Exploration Division, Kenneth Ledbetter is deputy associate administrator for programs, Dr. Thomas Morgan is Stardust program executive and program scientist.

At the Jet Propulsion Laboratory, Tom Duxbury is project manager. Bob Ryan is mission manager. JPL is a division of the California Institute of Technology, Pasadena, Calif.

At Lockheed Martin Space Systems, Denver, Colo., Joseph M. Vellinga is the company's Stardust program manager, and Dr. Benton C. Clark is the company's chief scientist for space exploration systems. Lockheed Martin Space Systems designed, built and operates the spacecraft, and will recover the sample return capsule.

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