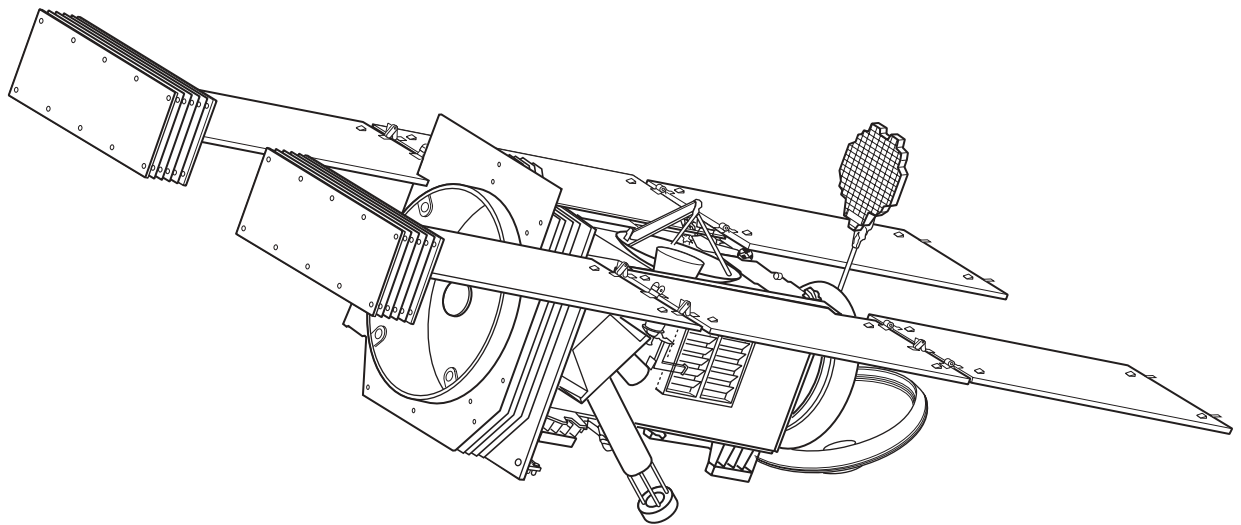


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

# Stardust Comet Flyby

Press Kit  
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## **GENERAL RELEASE:**

### **NASA COMET HUNTER CLOSING ON QUARRY**

Having trekked 3.2 billion kilometers (2 billion miles) across cold, radiation-charged and interstellar-dust-swept space in just under five years, NASA's Stardust spacecraft is closing in on the main target of its mission -- a comet flyby.

"As the saying goes, 'We are good to go,'" said project manager Tom Duxbury at NASA's Jet Propulsion Laboratory, Pasadena, Calif. "There are significant milestones ahead that we need to achieve before we reach the comet on Jan. 2, but we have a great team of engineers and scientists that have trained hard for this moment, and we have a spacecraft that is in great shape."

All this intense earthly preparation is directed at Wild 2 (pronounced Vilt-2), a ball of dirty ice and rock, about as big as 20 HMS Titanics laid end-to-end. Discovered in 1978, Wild 2 orbits the Sun once every 6.39 years on a trajectory that carries it nearly as close to the Sun as Mars is, and as far away from the Sun as Jupiter.

Though comet Wild 2 is the target, it is not the goal of Team Stardust to actually hit their target. Instead, Stardust is tasked to have a close encounter of the cometary kind. On Jan. 2 at 11:40:35 am PST, the 5.4-kilometer-wide (3.3-mile) comet will sail past the 5-meter-long (16-foot) Stardust spacecraft at a distance of about 300 kilometers (188 miles) and at a relative speed of 21,960 kilometers per hour (13,650 miles per hour). The plan is thus because Stardust is a sample return mission.

"In recent decades, spacecraft have passed fairly close to comets and provided us with excellent data," said Dr. Don Brownlee of the University of Washington, principal investigator for the Stardust mission. "Stardust, however, marks the first time that we have ever collected samples from a comet and brought them back to Earth for study."

Clad for battle behind specially designed armored shielding, Stardust will document its passage through the hailstorm of comet debris with two scientific instruments that will scrutinize the the size, number and composition of dust particles in the coma -- the region of dust and gas surrounding the comet's nucleus. Along with these insruments, the spacecraft's optical navigation camera will be active during the flyby and should provide images of the dark mass of the comet's nucleus. Data from all three will be recorded onboard Stardust and beamed back to Earth soon after the encounter.

The chain of events begins nine days out from the comet when Stardust deploys its "cometary catcher's mitt," a tennis-racket-shaped particle catcher of more than 1,000 square centimeters (160 square inches) of collection area filled with a material called aerogel. Made of pure silicon dioxide, like sand and 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.

"The samples we will collect are extremely small, 10 to 300 microns in diameter, and can only be adequately studied in laboratories with sophisticated analytical instruments," said Brownlee. "Even if a ton of sample were returned, the main information in the solids would still be recorded at the micron level, and the analyses would still be done a single grain at a time."

After the sample has been collected, the collector will fold down into a return capsule, which will close like a clamshell to secure the sample for a soft landing at the U.S. Air Force's Utah Test and Training Range in January 2006. The capsule, holding microscopic particles of comet and interstellar dust, will be taken to the planetary material curatorial facility at NASA's Johnson Space Center, Houston, Texas, where the samples will be carefully stored and examined.

Scientists believe in-depth terrestrial analysis of cometary samples will reveal a great deal not only about comets but also related to the earliest history of the solar system. Locked within the cometary particles is unique chemical and physical information that could provide a record of the formation of the planets and the materials from which they were made.

Stardust, a project under NASA's Discovery Program of low-cost, highly focused science missions, was built by Lockheed Martin Space Systems, Denver, Colo., and is managed by the Jet Propulsion Laboratory, Pasadena, Calif., for NASA's Office of Space Science, Washington, D.C. JPL is a division of the California Institute of Technology in Pasadena. More information on the Stardust mission is available at <http://stardust.jpl.nasa.gov> .

# Media Services Information

## **NASA Television Transmission**

NASA Television is carried on the satellite AMC-9, transponder 9C, at 85 degrees west longitude, vertical polarization. Frequency is on 3880.0 megahertz with audio on 6.8 megahertz. The schedule for Stardust Encounter television transmissions will be available from the Jet Propulsion Laboratory, Pasadena, Calif., and from NASA Headquarters, Washington.

## **Media Credentialing**

News media representatives who wish to cover the Stardust encounter with comet Wild 2 at NASA's Jet Propulsion Laboratory must be accredited through the JPL Media Relations Office. Journalists may phone the newsroom at 818/354-5011 for more information.

## **Briefings**

News briefings will be held at JPL before and after the encounter. Information about upcoming briefings will be available on the Internet as noted below.

## **Internet Information**

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 Jet Propulsion Laboratory's Stardust news website, <http://www.jpl.nasa.gov/stardust> . The Stardust project website is at <http://stardust.jpl.nasa.gov> .

# Quick Facts

## Spacecraft

Dimensions: Main bus 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. At time of comet flyby, solar panels will generate about 330 watts

## 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 Anfrank flyby: Nov. 2, 2002

Comet Wild 2 encounter: January 2, 2004

Earth-comet distance at time of encounter: 389 million kilometers (242 million miles)

Total distance traveled Earth to comet: 3.22 billion kilometers (2 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 and Training Range

Earth-comet distance at Earth landing: 860 million kilometers (534 million miles)

Total distance traveled comet to Earth: 1.14 billion kilometers (708 million miles)

Total distance traveled entire mission (Earth to comet to Earth): 4.37 billion kilometers (2.7 billion miles)

## Program

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



# Why Stardust?

Far 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 balls of ice, rocks and dust, they are the undercooked leftovers that remained after a sprawling cloud of gas and dust condensed to form the Sun and planets about 4.6 billion years ago. From time to time, the gravitational pull of a passing star 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 perhaps 1/50th the width of a human hair, these tiny particles are the pulverized flotsam of the galaxy, bits of ancient stars that exploded as they died. 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 oxygen.

These two niches bearing clues of the dawn of the solar system are the target for NASA's Stardust mission. The spacecraft will use a collector mechanism that employs 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 and when 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.) Most comets range in size from about 2 to 7 kilometers (1 to 5 miles) in diameter. Shields that protect the Stardust spacecraft from dust impacts were named for Whipple in honor of his role in cometary science.

If comets contain icy material, they must originate somewhere much colder than the relatively warm inner solar system. 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.

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 a belt of dormant comets lying just outside the orbits of the planets at perhaps 30 to 100 AU from the Sun; this has become known as the Kuiper Belt. Jupiter's gravity periodically influences one of these bodies to take up a new orbit around the Sun. The Oort Cloud, by contrast, would be the home 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.

In addition to the length of time between their visits, another feature distinguishes short- and long-period comets. 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. This suggests that the Kuiper Belt is a relatively flat belt, whereas the Oort Cloud is a three-dimensional sphere surrounding the solar system.

Where did the Oort Cloud and Kuiper Belt come from? Most astronomers now believe that the material that became comets condensed in the outer solar system around the orbits of Uranus and Neptune. Gravitational effects from those giant planets flung the comets outward.

Residing at the farthest reaches of the Sun's influence, comets did not undergo the same heating as the rest of the objects in the solar system, so they retain, largely unchanged, the original composition of solar system materials. As the preserved building blocks of the outer solar system, comets offer clues to the chemical mixture from which the planets formed some 4.6 billion years ago.

The geologic record of the planets shows that, about 3.9 billion years ago, a period of heavy comet and asteroid bombardment tapered off. The earliest evidence of life on Earth dates from just after the end of this heavy bombardment. The constant barrage of debris had vaporized Earth's oceans, leaving the planet too hot for the survival of fragile carbon-based molecules upon which life is based. Scientists therefore wonder: How could life form so quickly when there was so little liquid water or carbon-based molecules on Earth's surface? 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 replenishment of Earth's ocean after the vaporization of an early ocean during the late heavy bombardment. 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 are about 50 percent water by weight and

## Other Comet Missions

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

Past comet missions include:

- ❑ In 1985, NASA modified the orbit of the International Sun-Earth Explorer spacecraft to execute a flyby of Comet Giacobini-Zinner. At that point, the spacecraft was renamed **International Comet Explorer**. It successfully executed a flyby of comet Giacobini-Zinner in 1985 and comet 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 Borrelly and returned the best images and other science data taken from a comet to date.
- ❑ 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.

Future comet missions are:

- ❑ **Deep Impact** will purposely slam a 370-kilogram (approximately 820-pound) cylinder into a comet's nucleus so experts can study the interior of the comet. The launch of the Deep Impact spacecraft is planned for December 2004 and it is scheduled to reach out and touch its target, comet Tempel 1, on July 4, 2005.
- ❑ A European Space Agency mission, **Rosetta** will be launched in February 2004 to orbit comet 67P/Churyumov-Gerasimenko and deliver a science package to its surface via a lander. NASA is providing science instruments for the comet orbiter.

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 that came from a more water-rich part of the solar system.

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 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 fresh periodic comet -- meaning that it moves about the Sun in an elliptic orbit. In Wild 2's case that is once every 6.39 years. Its nucleus is thought to be of low density, with a diameter of about 5.4 kilometers (3.3 miles).

Until September 10, 1974, comet Wild 2's orbit lay between Jupiter and a point near Uranus. But on that date nearly 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 forever altered the comet's orbit, carrying it for the first time into the inner solar system. The new flight path carried 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 to get heated up, it loses some of its material through a process called sublimation. This happens when a solid becomes a vapor without first melting into a liquid. After about 1,000 trips past the Sun, a comet loses most of its volatile materials and no longer generates a coma, which is made up of the gases that escape off its surface. Since it is the escaping gases that drive the dust particles from the nucleus -- the solid part of the comet -- the comet no longer creates the long beautiful dust tail that we can sometimes see in the night sky.

An important aspect of Stardust's exploration of comet Wild 2 is that by the time Stardust encounters it, the comet will have 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.

Another important aspect is the comet's orbit. Stardust navigators were able to plot a flight path that allowed the spacecraft to encounter the comet at a relatively sedate closing speed. Because of this low-velocity meeting (passing each other at 6.1 kilometers per second, or about 13,600 miles per hour), the spacecraft can capture comet dust, rather than having it blow right through the collectors. The dust samples can then be brought back to the Earth to be analyzed.

## NASA's Discovery Program

Stardust is a mission under NASA's Discovery Program, which sponsors low-cost solar system exploration projects with highly focused science goals. Created in 1992, the Discovery Program competitively selects proposals submitted by teams led by scientists called principal investigators and supported by organizations which provide project management and 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 was launched in February 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 in December 1996 and reached Mars on July 4, 1997, demonstrating a unique way of landing with airbags to deliver a small robotic rover. Mars Pathfinder was managed by the Jet Propulsion Laboratory.

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

❑ Launched in August of 2001, **Genesis** is a mission that will return samples of solar wind particles. Principal investigator is Dr. Donald Burnett of the California Institute of Technology, with project management by the Jet Propulsion Laboratory. Genesis is NASA's first sample return mission since the Apollo moon landings ended in December of 1972.

❑ 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.

❑ **Messenger** will be launched in May 2004 and will enter Mercury orbit in July 2009, after three flybys of Venus along the way. Multiple flybys of the planet will provide opportunities for global mapping and detailed characterization of the surface, interior, atmosphere, and magnetosphere.

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❑ Scheduled for launch in December of 2004, Deep Impact is a spacecraft that will travel to comet Tempel 1 and release a small impactor, creating a crater in the side of the comet. The main spacecraft will measure and observe the gas released from the crater, to discover what makes up fresh comet material, and to understand what's inside a comet. The scheduled date for these celestial fireworks is July 4, 2005.

❑ Planned for launch in May 2006, Dawn will reach the asteroid Vesta in 2010 and the asteroid Ceres in 2014. These minor planets have remained intact since the earliest time of solar system formation. Their surfaces are believed to contain a snapshot of the conditions present in the solar system's first 10 million years, allowing Dawn to investigate both the origin of the solar system and its present state.

❑ Planned for launch in the fall of 2007, Kepler will monitor 100,000 stars similar to our Sun for four years. Kepler could detect many habitable, Earth-size planets and provide a stepping stone to the next extensive search for habitable planets and life.

❑ The Analyzer of Space Plasma and Energetic Atoms, or Aspera 3, is one of seven scientific instruments flying aboard the Mars Express spacecraft. NASA is contributing hardware and software to the instrument, led by Sweden's Institute of Space Physics. Mars Express is a European Space Agency mission scheduled to enter Martian orbit in late December 2003.

## **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 constant flow of particles -- each about a micron in size, or 1/50th 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.

Scientists believe that 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.

As the Sun orbits the galactic center, it cuts through the dust like a ship passing through waves. 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. Outward pressure from the solar wind sweeps the inner solar system near Earth clean, but interstellar dust is more easily detected beyond the orbit of Mars.

Interstellar dust provided the building blocks for solid materials on Earth and other planets. In the life cycle of stars, light elements such as hydrogen coalesce to form the star, which in time develops enough mass to burst into an ongoing nuclear reaction. Many stars die in a spectacular explosion, converting light elements into heavier elements. 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 many different types, including red giants, carbon stars, novae and supernovae. 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 radioactive signatures of the environment 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 collected and studied dust in the stratosphere and in Earth orbit. Since the late 1960s, collections of ocean sediment have brought up microscopic glass and metallic spherules, space particles that melted during atmospheric entry. The sample of interstellar dust returned by Stardust will be compared with these and others to help define 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 many similarities 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 samples will be small and partly eroded, they will 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 will make observations and measurements of Wild 2 from mid to late December 2003. These observations will assist the Stardust team in validating the size of coma and amount of activity taking place on comet Wild 2, as well as assist in further reducing any errors in the plotting of the comet's orbit.



# Mission Overview

Launched in 1999, the Stardust spacecraft will loop a total of three times around the Sun over seven years before it returns to Earth in 2006. On the way to its comet encounter, it collected interstellar dust on two different solar orbits. On Jan. 2, 2004, Stardust will fly through the coma, or cloud of dust and debris, surrounding comet Wild 2. Finally the spacecraft will approach Earth, ejecting an entry capsule that will descend into the U.S. Air Force's Utah Test and Training Range carrying 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; maximizes the time for favorable collection of interstellar dust; and makes 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 its position was properly aligned; 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 on the latter part of that first orbit, it passed through a region where interstellar particles flow through the solar system. From February through May 2000, the spacecraft deployed its collector to capture these interstellar particles. One part of collector mechanism called its "B side" was employed to collect the particles, reserving the other half, called the "A side," for the spacecraft's later dust collection mission at comet Wild 2.

The spacecraft completed its first solar orbit when it flew by the Earth on Jan. 15, 2001. The flyby altitude at its closest approach distance was approximately 6,008 kilo-

meters (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 latter part of its second orbit, Stardust again exposed the "B side" of its collector to interstellar particles flowing through the solar system. Then, in December 2002, Stardust concluded its second and final collection period of interstellar particles. 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 Anfrank. This encounter took place on Nov. 2, 2002, and was used as an engineering test of the ground and spacecraft operations that will be implemented at the primary scientific target, comet Wild 2.

### **Comet Flyby Overview**

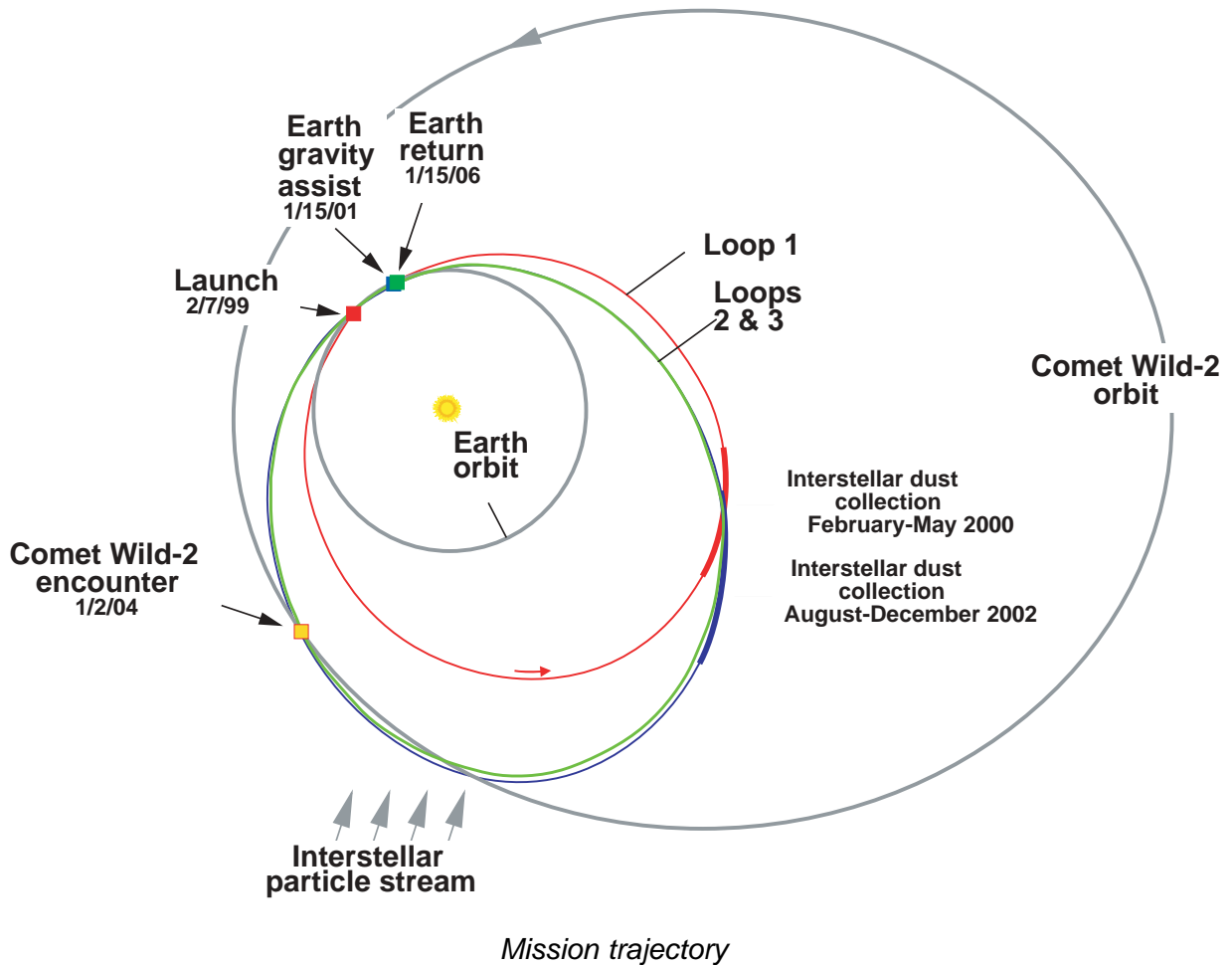
On Jan. 2, 2004, at about 11:41 a.m. PST (2:40 p.m. EST), after traveling the solar system for almost four years -- and 3.22 billion kilometers (2 billion miles) -- the Stardust spacecraft will make its closest approach to comet Wild 2 as the comet sails past Stardust at a relative speed of 21,960 kilometers per hour (13,650 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.

The passage through the most intensive rain of cometary particles within the coma is expected to last about 8 minutes. Within minutes after the closest approach, Stardust will begin to transmit images and other scientific data collected and stored in its computer memory during the flyby.

### **Flyby Miss Distance**

Planning for the near-miss of a 5.4-kilometer-wide (3.4-mile) comet and a 4.8-meter-long (15.9-foot) spacecraft closing on each other at a velocity much faster than any rifle bullet -- all while 389 million kilometers (242 million miles) away from home -- is a fulltime job. The flight team was tasked to come up with a flight plan that balances the maximum opportunity for collecting the freshest cometary particles off the comet's nucleus while providing the greatest likelihood of keeping the spacecraft out of harm's way.

Defining "harm's way" in an environment as astronomically foreign as the coma of a comet is a challenge, to say the least. To help understand the hazards posed by the flyby, scientists and engineers developed a dust model for Wild 2. This model spells out the team's best estimates for the location, quantity and size of the dust surrounding



the comet's nucleus. Stardust's managers have been carefully weighing this information as they fine-tune the "miss distance" for the spacecraft's pass by the comet.

Based on the that analysis, mission managers established a miss distance of 300 kilometers (about 186 miles). That distance, however, can be tweaked as late as Dec. 31, 2003 -- just two days before the flyby -- when the spacecraft fires its thrusters to fine-tune its trajectory for the encounter. The team will gather images taken by Stardust's navigation camera, as well as data from ground-based observatories, to help make a final decision on the comet flyby distance.

### Encounter Sequences

For planning purposes, the Stardust mission team has defined the spacecraft's encounter of comet Wild 2 as a 119-day period spanning from 88 days prior to comet flyby to 31 days after. This encounter is further divided into five time segments during which various mission activities are planned:

- Far Encounter: Minus 88 days to minus 1 day
- Near Encounter: Minus 1 day to minus 5 hours
- Close Encounter: Minus 5 hours to plus 5 hours
- Closest Encounter: Minus 360 seconds to plus 360 seconds
- Post Encounter: Encounter day to plus 31 days

### **Far Encounter: Minus 88 Days to Minus 1 Day**

During this phase, the Stardust team has been using the spacecraft's navigation camera to scour the skies in the area where they expected to find Wild 2. Acquiring the comet visually is considered of paramount importance for a successfully executed flyby, as it will further refine knowledge of the exact location and orbit of the comet.

On Nov. 13, 2003, some 50 days before the encounter, an important milestone was passed when Wild 2 was detected by the spacecraft's navigation camera, several weeks earlier than anticipated. These initial images and later images leading up to encounter are used by navigators to help plan thruster firings to fine-tune Stardust's flight path.

During the final month of the spacecraft's approach to the comet, thruster firings have been scheduled to take place Dec. 3, Dec. 23 and Dec. 31, 2003, as well as on Jan. 2, 2004 (Jan. 1 PST). The Dec. 31 maneuver will set Stardust's final targeted miss distance, and also change the spacecraft's orientation, or "attitude," so that its protective shields will safeguard Stardust from the onslaught of cometary particles. The Jan. 2 thruster firing will clean up any execution errors from the previous maneuver and improve targeting precision.

On Dec. 24, when it is 9 days out, Stardust's schedule calls for it to deploy its aerogel-laden collector grid with the "A side" facing the direction of incoming comet particles. After a heat shield is removed from the sample return capsule's opening, the collector emerges from the capsule and is extended fully sticking above the spacecraft's shielding exposed to the stream of comet particles. The sequence will take about 30 minutes to complete.

### **Near Encounter: Minus 1 Day to Minus 5 Hours**

As the spacecraft nears the comet, it will take pictures of the comet more frequently, and spend more time transmitting these images to Earth. To support the increased data traffic, ground stations of the Deep Space Network will be in touch with Stardust continuously during these hours.

Around 5:18 p.m. PST on Jan. 1, the spacecraft will fire its thrusters for a final time before encountering the comet. After this maneuver, the spacecraft will roll back to its protective "encounter attitude" or orientation.

## Close Encounter Milestones

*Jan. 2-3, 2004*

- 5:49 a.m. Jan. 2.: "Encounter sequence" of onboard computer commands begins
- 6:19 a.m.: Cometary and interstellar dust analyzer instrument configured
- 9:19 a.m.: Navigation camera takes approach image
- 10:19 a.m.: Navigation camera takes approach image
- 11:04 a.m.: Dust flux monitor instrument turned on
- 11:12 a.m.: Stops sending data, transmits carrier signal only
- 11:13 a.m.: Final roll maneuver to adjust encounter orientation or "attitude"
- 11:19 a.m.: Closest approach to comet
- 11:25 a.m.: Navigation camera ends period of highest frequency imaging
- 11:25 a.m.: Roll maneuver to take spacecraft out of encounter orientation
- 11:26 a.m.: Resumes sending data instead of carrier signal
- 11:27 a.m.: Navigation camera takes final picture
- 11:29 a.m.: Navigation camera turned off
- 11:36 a.m.: Begins transmitting images, dust flux monitor data
- 5:19 a.m. Jan. 3: Cometary and interstellar dust analyzer returned to cruise mode
- 5:19 a.m.: "Encounter sequence" of computer commands ends

*All times listed as actual event time at the spacecraft, in Pacific Standard Time. Signals confirming each event will take 20 minutes to reach Earth.*

### **Close Encounter: Minus 5 Hours to Plus 5 Hours**

In all of Stardust's journey spanning almost seven years, the majority of scientific data will be collected in a period of just 10 hours -- what mission managers call the "close encounter." As this time window opens, when the spacecraft is about 100,000 kilometers (60,000 miles) away from the nucleus, Stardust will begin to enter the comet's coma. Because of its flight path, it will enter the coma in front of the nucleus as it flies through the halo of gases and dust at the head of comet Wild 2.

During this phase the comet's nucleus should begin to emerge in the navigation camera's field-of-view as an extended dark body. At 30 minutes out, the navigation camera will begin taking images at the rate of nearly one every 30 seconds. Over the next 38 minutes, 72 images will be stored in the spacecraft's computer memory. Fifteen minutes before closest approach, the spacecraft will turn on its dust flux monitor.

### **Closest Encounter: Minus 360 Seconds to Plus 360 Seconds**

Stardust will be flying through the most concentrated region of cometary particles at this point. At 5 minutes out, the navigation camera will increase its rate of picture-taking to one every 10 seconds. This rate will continue for the next 10 minutes.

Comet Wild 2 is flying through space faster than the spacecraft is. To pull off the encounter, navigators had to calculate a location in time and space where the spacecraft needed to be so that the comet could essentially "run over" it. Navigators were further tasked to have this brief meeting of spacecraft and comet occur on the sunlit side of the comet, so that the Sun could act as a natural flashbulb for picture-taking and because that is where the majority of comet particles are expected to be found.

The comet will approach Stardust from outside and below the spacecraft's orbital plane. At this point the spacecraft will be flying "backwards" with its nose pointed down so its defensive shielding can protect it from the expected hailstorm of particles. The comet will overtake the spacecraft and continue on its orbital path, which will carry it above and inside the trajectory of Stardust.

One major challenge for Stardust's mission designers was to figure out a way to keep the comet nucleus within the navigation camera's field-of-view during encounter. To accomplish this, they programmed the navigation camera's scanning mirror to gradually pan as the comet passes by. During closest encounter, the spacecraft will perform a roll to keep the camera pointed at the comet.

This roll, lasting about 30 seconds, could result in loss of the signal from the spacecraft's high-gain antenna. To minimize the chance of loss of signal during this maneuver, mission planners will command the spacecraft's medium-gain antenna to take over from the high-gain dish during the 12 minutes surrounding closest encounter. The spacecraft will stop sending scientific or engineering data and instead will transmit a simple carrier signal during this closest passage. After the 12 minutes of closest encounter are over, the spacecraft will roll to point its high-gain antenna at Earth once again, and will resume transmitting encoded data.

As Stardust flies through the most concentrated region of cometary particles, its dust flux monitor instrument will be logging 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 will be performing instantaneous compositional analysis of material and also storing its results in the spacecraft's onboard memory.

### **Post-Encounter: Flyby Day to Plus 31 Days**

After pointing its high-gain antenna at Earth once again, Stardust will use its navigation camera to take one parting snapshot of Wild 2. Selected images and other science and engineering data recorded onboard during the coma fly-through will begin to be transmitted to Earth.

About five hours after closest approach, the sample collector with its cometary pickings will begin a 30-minute process of stowing itself. After the sample return capsule's lid closes, it will remain sealed until Earth return in January 2006.

## Earth Return

Stardust is scheduled to use its thrusters to fine-tune its flight path three times as it makes its final return to Earth on January 15, 2006. These maneuvers are scheduled 13 days, one day and 12 hours before Earth entry, respectively.

Soon after the final trajectory maneuver at an altitude of 110,728 kilometers (68,805 miles), Stardust will release its sample return capsule. A spring mechanism will impart a spin to the capsule as it is pushed away from the spacecraft in order to stabilize it. After the capsule has been released, the main spacecraft will perform a maneuver to divert itself to avoid entering Earth's atmosphere. The spacecraft will remain in orbit around the Sun.

The capsule will enter Earth's atmosphere at a velocity of approximately 12.8 kilometers per second (28,600 miles per hour). The capsule's aerodynamic shape and center of gravity are designed like a badminton shuttlecock so that the capsule will automatically orient itself with its nose down as it enters the atmosphere.

As the capsule descends, its speed will be reduced by friction on its heat shield, a 60-degree half-angle blunt cone made of a graphite-epoxy composite covered with a new, lightweight thermal protection system.

The capsule will slow to a speed about 1.4 times the speed of sound at an altitude of about 30 kilometers (100,000 feet), at which time a small pyrotechnic charge will be fired, releasing a drogue parachute. After descending to about 3 kilometers (10,000 feet), a line holding the drogue chute will be cut, allowing the drogue to pull out a larger parachute that will carry the capsule to its soft landing. At touchdown, the capsule will be traveling at approximately 4.5 meters per second (14.8 feet per second), or about 16 kilometers per hour (10 miles per hour). In all, about 10 minutes will elapse between the beginning of the entry into Earth's atmosphere until the parachute is deployed.

The landing site at the Utah Test and Training Range near Salt Lake City was chosen because the area is a vast, desolate and unoccupied salt flat controlled by the U.S. Air Force in conjunction with the U.S. Army. The landing footprint for the sample return capsule will be about 30 by 84 kilometers (18 by 52 miles), an ample space to allow for aerodynamic uncertainties and winds that might affect the direction the capsule travels in the atmosphere. To land within the footprint, the capsule's trajectory must achieve an entry accuracy of 0.08 degree. The sample return capsule will approach the landing zone on a heading of approximately 122 degrees on a northwest to southeast trajectory. Landing time will take place at about 3 a.m. Mountain Standard Time on January 15, 2006.

The actual landing footprint will be predicted by tracking the spacecraft just before the

capsule's release. Roughly six hours before entry, an updated footprint will be provided to the capsule recovery team.

## **Ground Recovery**

A UHF radio beacon on the capsule will transmit a signal as the capsule descends to Earth, while the parachute and capsule will be tracked by radar. A helicopter will be used to fly the retrieval crew to the landing site. Given the small size and mass of the capsule, mission planners do not expect that its recovery and transportation will require extraordinary handling measures or hardware other than a specialized handling fixture to cradle the capsule during transport.

## **Sample Curation**

Once the sample return capsule is recovered, its contents will be immediately transported to its final destination, the planetary material curatorial facility at NASA's Johnson Space Center in Houston. The Johnson Space Center's curation laboratory is a special facility designed for payload cleaning and curation of samples returned from space missions. It includes facilities for the Apollo lunar samples, Antarctic meteorites, cosmic dust, samples from NASA's Genesis mission collecting solar particles, hardware exposed to the environment of space.

The laboratory consists of numerous cleanrooms maintained at varying degrees of cleanliness. The laboratory currently being developed for Stardust samples will be class 100. A class 100 cleanroom maintains less than 100 particles larger than 0.5 microns in each cubic foot of air space (or about 3,530 particles per cubic meter of air).

Once safely at the curation laboratory, technicians will open the Stardust sample return capsule. The aerogel and its collection of comet and interstellar dust will be inspected, extracted, characterized, and made available to the scientific community for analysis.

The Stardust curation team has developed exacting techniques for the removal and analysis of captured grains from the silica aerogel in which it is embedded. They will continue to improve and practice these techniques before the comet samples are in their hands in 2006.

Most particles from a comet are smaller than the diameter of a human hair. The expected total mass of the sample returned by Stardust will probably be about 1 milligram -- less than a thimbleful. 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 (1/50th 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.

## **Planetary Protection**

The U.S. is a signatory to the United Nations' 1966 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."

Comets are believed to be primordial bodies made up of material that is virtually unchanged since their creation when the solar system formed 4.6 billion years ago. This means that any evolutionary processes leading to the emergence of life have not occurred. There is no scientific reason to believe that bacteria or viruses or any other life exist on comets. One of the objectives of the Stardust mission is to investigate whether the chemical building blocks of life exist on comets. But even if such building blocks do reside there, comets have not provided the hospitable environment required over millions of years to accommodate the complex processes that could result in the emergence of even single-celled organic life.

On Stardust, all comet particles that are collected will be heated to extremely high temperature due to their impact speed on the aerogel collector. The temperature caused by the compression interaction between the aerogel and any given particle is calculated to be at least 1,000 C (roughly 1,800 F). In fact, the collector material literally melts to encapsulate the captured particles. Such high temperatures are naturally sterilizing. As a particle hits the aerogel sample collector, it will come to a dead stop within a microsecond, having traveled about 3 centimeters (1.2 inches) into the aerogel. By that point, the aerogel, which is silica-based, will have melted around the particle, trapping it in glass.

It should be noted that particles from space, including material from comets, fall onto Earth's surface at a rate of approximately 40,000 tons per year, and some of this material is believed to survive atmospheric entry without severe heating.

## **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 JPL. The lettering on the microchips is so small that about 80 let-

ters 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, D.C., as a tribute to those who died in that war.

# 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 will also be obtained without dedicated hardware. The navigation camera, for example, will provide images of the comet both for targeting accuracy and scientific analysis.

## **Aerogel Dust Collectors**

To collect particles without damaging them, Stardust will use 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 1930 by a researcher at the College of the Pacific in Northern California, aerogel is made from fine silica mixed with a solvent. The mixture is set in molds of the desired shape and thickness, and then pressure-cooked at high temperature.

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 flies through the comet's coma, the impact velocity of particles as they are captured will be up to six times the speed of a bullet fired from a high-powered rifle. The Whipple shields can protect the spacecraft from impacts of particles the size of a pea, but larger particles present a more severe hazard.

Although the particles captured in aerogel will each be smaller than a grain of sand, high-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 will bury 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 about a micron (a millionth of a meter, or 1/25,000th of an inch, or about 1/50th of the width of a human hair) to 100 microns (a tenth of a millimeter, or 1/250th of an inch, or about twice the width of a human hair). Stardust scientists anticipate that the aerogel will collect a few particles at the upper end of this size range, and many more particles in the submicron range. 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 each particle will be probed for years in research labs.

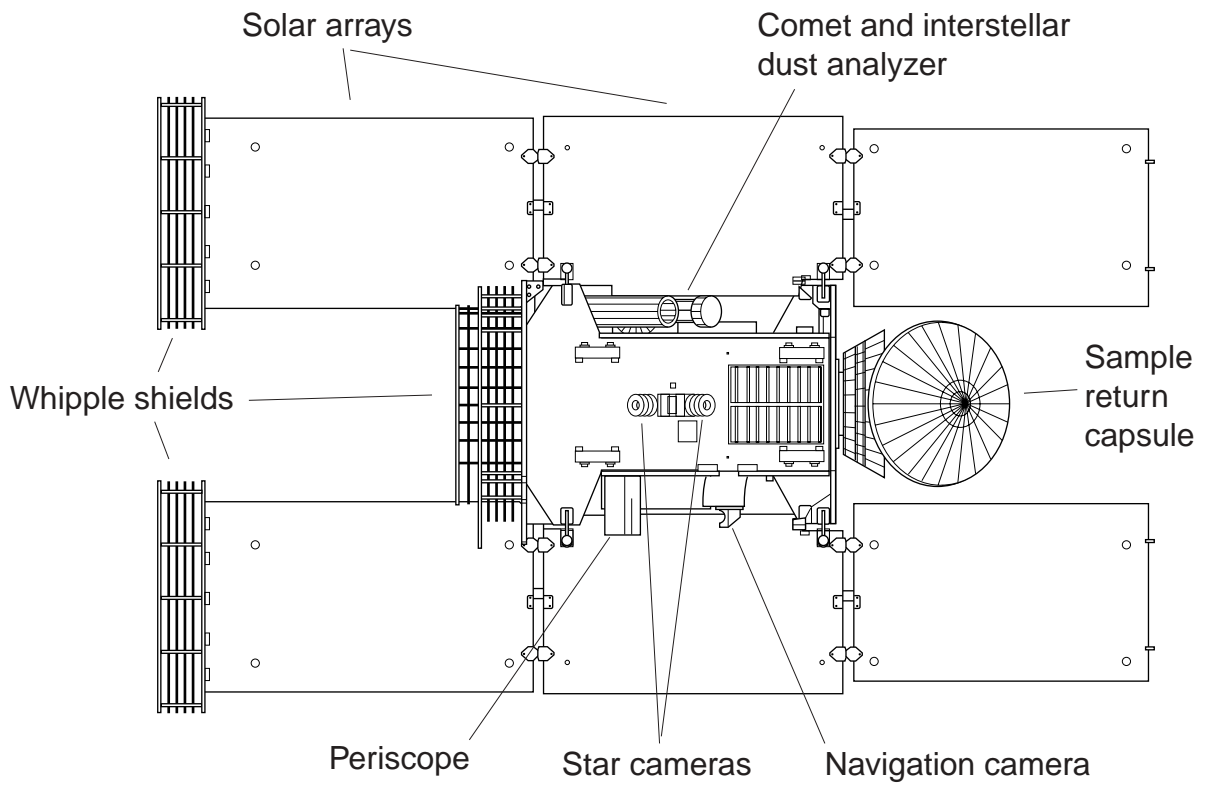
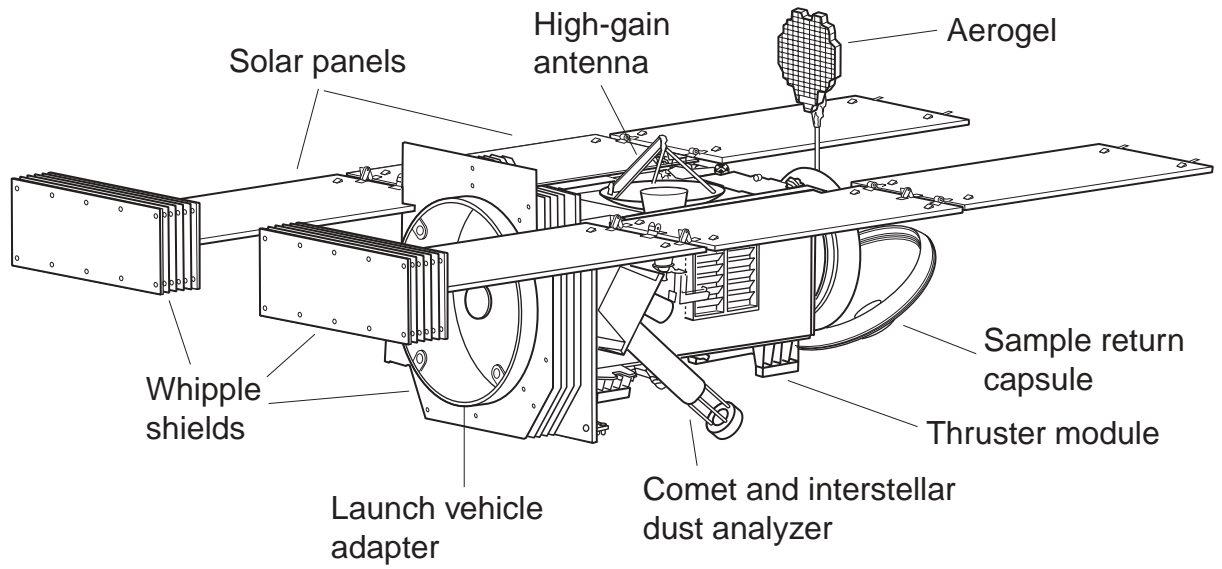
One side of the dust collection module, called the "A side", will be used for the comet encounter, while the opposite side ("B side") will be used for interstellar collection. More than 1,000 square centimeters (160 square inches) of collection area is provided on each side. Each of Stardust's two collectors has 130 rectangular blocks of aerogel 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 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 will fold 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



*Stardust spacecraft*

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 will study the chemical composition of particulates in the coma of comet Wild 2.

The purpose of the analyzer instrument is to intercept and perform instantaneous compositional analysis of dust as it is encountered by the spacecraft. Data will be transmitted to Earth as soon as a communication link is available.

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 will provide 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 will detect 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 will take 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 is tracked and several images taken with a rotating mirror that no longer views through the periscope.

## **Propulsion System**

The Stardust spacecraft needs only a relatively modest propulsion system because it is on a low-energy trajectory for its flyby of comet Wild 2 and subsequent return to Earth, and because it was aided by a gravity-assisted boost maneuver when it flew past Earth in January 2001.

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 will be 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. When Stardust flies by the comet, it will be carrying about 31 kilograms (68.3 pounds) of fuel. This is well within the mission's fuel budget.

## **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 will 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 22,000 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 will protect Stardust from the blast of cometary particles is named for American astronomer Dr. Fred L. Whipple, who in 1950 accurately predicted the "dirty snowball" model of the cometary nucleus as a mixture of dark organic material, rocky grains and water ice. Whipple came up with the idea of shielding spacecraft from high-speed collisions of the bits and pieces that are ejected from comets 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.

## 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 heat shield is made of a graphite-epoxy composite covered with a thermal protection system. 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 also made of a graphite-epoxy composite 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 backshell 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 backshell 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 cut the drogue chute from the capsule at an altitude of approximately 3 kilometers (10,000 feet). As the drogue chute moves away, it will extract the 8.2-meter-diameter (27-foot) main chute from the canister. Upon touchdown, cutters will fire to cut the main chute cables 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 bea-

con 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 40 hours.

# Science Objectives

The primary goal of the Stardust mission is to collect samples of a comet's coma and return them to Earth. In addition, interstellar dust samples will be gathered en route to the comet.

In laboratories, the samples will be scrutinized to understand their elemental makeup; presence of isotopes; mineralogical and chemical properties; and possible biogenic properties.

During the encounter itself, comet dust will be studied by a mass spectrometer. This instrument will provide data on organic particle materials that might not survive aerogel capture. Since an identical instrument flew on the European Space Agency's Giotto spacecraft during its comet Halley flyby in 1986, data from the two missions can be compared to understand how different comets compare and contrast.

During selected portions of its cruise phase, Stardust collected interstellar grains now passing through the solar system. Interstellar gas samples should also be absorbed in the aerogel, allowing direct measurement of isotopes of elements such as helium and neon.

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

## Stardust Science Team

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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 interstellar grains that constitute most of the solid matter in the galaxy, and they will provide a highly intimate view of both pre-solar dust and nebular condensates contained in comets. Such materials will be compared with primitive meteorites and interplanetary dust samples to understand the solids involved in solar system formation, the solids that existed in the outer regions of the nebula where comets formed, and solids in the inner regions of the nebula where asteroids formed. The data will provide fundamental insight into the materials, processes and environments that existed during the origin and early evolution of the solar system.

Interstellar grains are currently studied mainly 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 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. The interstellar grains that have been identified in meteorites are predominantly grains that formed in gas flows from carbon-rich stars such as red giants and what are called ABG stars, while the more typical grains from oxygen-rich stars have not been found. 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 and 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.

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 exobiology. 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 iridium in rocks at Earth's Cretaceous-Tertiary geologic layer marking the end of the age of the dinosaurs about 65 million years ago has, along with other evidence, raised the probability that an impact of an asteroid-sized body with Earth was responsible for the demise of the giant creatures. 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.

# Program/Project 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 Office of Space Science, Washington. At NASA Headquarters, Dr. Edward Weiler is associate administrator for space science. Orlando Figueroa is the director of NASA's Solar System Exploration Division, Kenneth Ledbetter is deputy associate administrator for programs, Barry Geldzahler is Stardust program executive, and Dr. Thomas Morgan is Stardust 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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