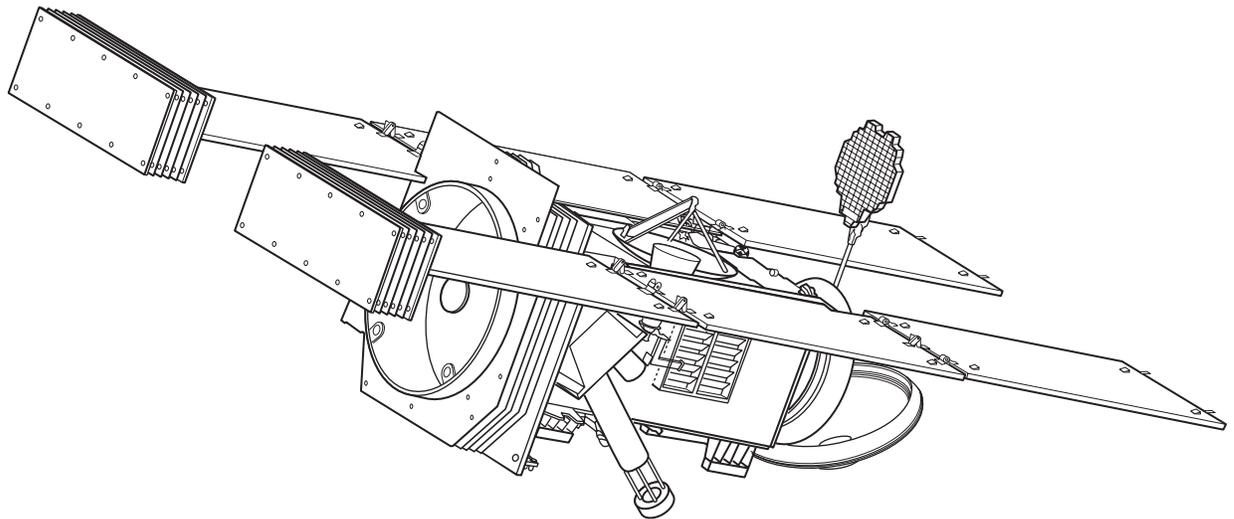


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Stardust Launch

Press Kit
February 1999



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RELEASE:

STARDUST MISSION SET TO BRING BACK A PIECE OF A COMET

NASA's Stardust mission, scheduled for launch February 6, 1999 from Cape Canaveral, FL, will send a spacecraft flying through the cloud of dust that surrounds the nucleus of a comet – and, for the first time ever, bring cometary material back to Earth.

Comets, which periodically grace our sky like celestial bottle rockets, are thought to hold many of the original ingredients of the recipe that created the planets and brought plentiful water to Earth. They are also rich in organic material, which provided our planet with many of the ready-to-mix molecules that could give rise to life. They may be the oldest, most primitive bodies in the solar system, a preserved record of the original nebula that formed the Sun and the planets.

"Scientists have long sought a sample directly from a known comet because of the unique chemical and physical information these bodies contain about the earliest history of the solar system," said Dr. Edward Weiler, NASA's associate administrator for space science. "Locked within comet molecules and atoms could be the record of the formation of the planets and the materials from which they were made."

Stardust is the first U.S. mission dedicated solely to a comet and will be the first to return extraterrestrial material from outside the orbit of the Moon. Stardust's main objective is to capture a sample from a well-preserved comet called Wild-2 (pronounced "Vilt-2").

The spacecraft will also collect interstellar dust from a recently discovered flow of particles that passes through our solar system from interstellar space. As in the proverbial "from dust to dust," this interstellar dust represents the ultimate in recycled material; it is the stuff from which all solid objects in the universe are made, and the state to which everything eventually returns. Scientists want to discover the composition of this "stardust" to determine the history, chemistry, physics and mineralogy of nature's most fundamental building blocks.

Because it would be virtually impossible to equip a spacecraft with the most sophisticated lab instrumentation needed to analyze such material in space, the Stardust spacecraft is more of a robotic lab assistant whose job it is pick up and deliver a sample to scientists back on Earth. The spacecraft will, however, radio some on-the-spot analytical observations of the comet and interstellar dust.

"The samples we will collect are extremely small, less than a micron, or 1/25,000th of an inch, in size, and can only be adequately studied in laboratories with sophisticated analytical instruments," said Dr. Donald C. Brownlee of the University of Washington, principal investigator for the Stardust mission.

"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."

Stardust will meet up with Comet Wild-2 on January 2, 2004. A gravity assist flyby of Earth will put Stardust on a trajectory that will allow it to capture cometary dust intact at a low relative speed of 6.1 kilometers per second (about 13,600 miles per hour). An onboard camera will aid in navigating the spacecraft as close as about 150 kilometers (100 miles) from the comet's nucleus, permitting the capture of the freshest samples from the heart of the comet.

Dressed for survival behind armored shields, Stardust will document its 10-hour passage through the hailstorm of comet debris with scientific instruments and the navigation camera. On approach to the dust cloud, or "coma," the spacecraft will flip open a tennis-racket-shaped particle catcher filled with a smoke-colored glass foam called aerogel to capture the comet particles. Aerogel, the lowest-density material in the world, has enough "give" in it to slow and stop particles without altering them too much. After the sample has been collected, the aerogel capturing device will fold down into a return capsule, which closes like a clamshell to enclose the sample for its safe delivery to Earth.

In addition, a particle impact mass spectrometer will obtain in-flight data on the composition of both cometary and interstellar dust, especially very fine particles. The optical navigation camera should provide excellent images of the dark mass of the comet's nucleus. Other equipment will reveal the distribution in both time and space of coma dust, and could give an estimate of the comet's mass.

On January 15, 2006, a parachute will set the capsule gently onto the salt flats of the Utah desert for retrieval. The scientifically precious samples can be studied for decades into the future with ever-improving techniques and analysis technologies, limited only by the number of atoms and molecules of the sample material available. Many types of analyses now performed on lunar samples, for example, were not even conceived at the time of the Apollo missions to the Moon.

Comets are small, irregularly shaped bodies composed of a mixture of grains of rock, organic molecules and frozen gases. Most comets are about 50 percent water ice. Typically ranging in size up to about 10 kilometers (6 miles) in diameter, comets have highly elliptical orbits that bring them close to the Sun and then swing them back out into deep space. They spend most of their existences in a deep freeze beyond the orbit of Pluto – far beyond the Sun's dwindling influence, which is why so much of their original material is well-preserved.

When a comet approaches within about 700 million kilometers (half billion miles) of the Sun, the surface of the nucleus begins to warm, and material on the comet's nucleus heats and begins to vaporize. This process, along with the loss of rocky debris or other particles that fly off the surface, creates the cloud around the nucleus called the coma. It is the glowing, fuzzy coma that appears as the head of a comet when one is observed from Earth. A tail of luminous debris and another, less apparent, tail of gases flow millions of miles beyond the head in the direction away from the Sun.

Comet Wild-2 is considered an ideal target for study because, until recently, it was a long-period comet that rarely ventured close to the Sun. A fateful pass near Jupiter and its enormous gravity field in 1974 pulled Comet Wild-2 off-course, diverting it onto a tighter orbit that brings it past the Sun more frequently and also closer to Earth's neighborhood. Because Wild-2 has only recently changed its orbit, it has lost little of its original material when compared with other short-period comets, so it offers some of the best-preserved comet samples that can be obtained.

Stardust was competitively selected in the fall of 1995 under NASA's Discovery Program of low-cost, highly focused science missions. As a Discovery mission, Stardust has met a fast development schedule, uses a small Delta launch vehicle, is cost-capped at less than \$200 million, and is the product of a partnership involving NASA, academia and industry.

Principal investigator Brownlee is well-known for his discovery of cosmic particles in Earth's stratosphere known as Brownlee particles. Dr. Peter Tsou of NASA's Jet Propulsion Laboratory, Pasadena, CA, an innovator in aerogel technology and maker of aerogel, serves as deputy investigator. JPL, a division of the California Institute of Technology, manages the Stardust mission for NASA's Office of Space Science, Washington, DC. Dr. Kenneth L. Atkins of JPL is project manager. The spacecraft is designed, built and operated by Lockheed Martin Astronautics, Denver, CO. JPL provided the spacecraft's optical navigation camera, and the Max Planck Institute of Germany provided the real-time dust composition analyzer.

[End of General Release]

Media Services Information

NASA Television Transmission

NASA Television is broadcast on the satellite GE-2, transponder 9C, C band, 85 degrees west longitude, frequency 3880.0 MHz, vertical polarization, audio monaural at 6.8 MHz. The schedule for television transmissions for the Stardust launch will be available from the Jet Propulsion Laboratory, Pasadena, CA; Johnson Space Center, Houston, TX; Kennedy Space Center, FL, and NASA Headquarters, Washington, DC.

Status Reports

Status reports on mission activities for Stardust will be issued by the Jet Propulsion Laboratory's Media Relations Office. They may be accessed online as noted below. Audio status reports are available by calling (800) 391-6654 or (818) 354-4210.

Launch Media Credentialing

Requests to cover the Stardust launch must be faxed in advance to the NASA Kennedy Space Center newsroom at (407) 867-2692. Requests must be on the letterhead of the news organization and must specify the editor making the assignment to cover the launch.

Briefings

An overview of the mission will be presented in a news briefing broadcast on NASA Television originating from NASA Headquarters in Washington, DC, at 2 p.m. EST January 13, 1999. A pre-launch briefing at Kennedy Space Center is scheduled the day before launch.

Internet Information

Extensive information on Stardust, including an electronic copy of this press kit, press releases, fact sheets, status reports and images, is available from the Jet Propulsion Laboratory's World Wide Web home page at <http://www.jpl.nasa.gov/> . The Stardust mission also maintains a home page 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, consisting of 254-kg (560-lb) spacecraft and 46-kg (101-lb) return capsule, plus 85 kg (187 lbs) fuel
Power: Solar panels providing from 170 to 800 watts, depending on distance from Sun

Launch Vehicle

Type: Delta II (model 7426) with Star 37 upper stage

Mission

Launch period: February 6-25, 1999 from Cape Canaveral Air Station, FL
Daily launch opportunity: Near-instantaneous; 4:07 p.m. EST on February 6 (time varies on other days)
Earth-comet distance at time of launch: 820 million kilometers (508 million miles)
Interstellar dust collection: March-May 2000, July-December 2002
Earth gravity assist flyby: January 15, 2001
Altitude at Earth gravity assist: 5,964 kilometers (3,706 miles)
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: 3.7 billion kilometers (2.3 billion miles)
Spacecraft speed relative to comet at closest approach: 21,960 km/h (13,650 mph)
Earth return: January 15, 2006
Landing site: U.S. Air Force Utah Test and Training Range
Earth-comet distance at time of Earth landing: 860 million kilometers (534 million miles)
Total distance traveled comet to Earth: 1.5 billion kilometers (930 million miles)
Total distance traveled entire mission (Earth to comet to Earth): 5.2 billion kilometers (3.2 billion miles)

Program

Cost: \$128.4M spacecraft development, \$37.2M mission operations; total \$165.6 million (not including launch vehicle)

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 per-

fect 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. Also 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, 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

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 (ISEE) spacecraft to execute a flyby of Comet Giacobini-Zinner. The spacecraft was renamed **International Comet Explorer (ICE)**.
- 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.

Future comet missions are:

- Comet Nucleus Tour (Contour)** will take images and comparative spectral maps of three comets – Encke, Schwassmann-Wachmann-3 and d'Arrest – following launch in July 2002.
- Deep Space 4/Champollion** will perform the first landing on a cometary nucleus and demonstrate technologies for collecting samples when it reaches Comet Tempel 1 following launch in 2003.
- A European Space Agency mission, **Rosetta** will be launched in 2003 to orbit Comet Wirtanen and deliver a surface science package to the comet's surface. NASA is providing science instruments for the comet orbiter.

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

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:

❑ **Near Earth Asteroid Rendezvous (NEAR)** was launched in February 1996 and is scheduled to become the first spacecraft to orbit an asteroid when it reaches Eros in February 2000. NEAR is 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 60 miles (100 kilometers). Principal investigator is Dr. Alan Binder of the Lunar Research Institute, Gilroy, CA, with project management by NASA's Ames Research Center.

❑ **Genesis** is a mission that will return samples of solar wind particles following launch in January 2001. Principal investigator is Dr. Donald Burnett of the California Institute of Technology, with project management by the Jet Propulsion Laboratory.

❑ **Comet Nucleus Tour (Contour)** will be launched in July 2002 to execute close flybys of three comets – Encke, Schwassmann-Wachmann-3 and d'Arrest. Principal investigator is Dr. Joseph Veverka of Cornell University, with project management by Johns Hopkins University's Applied Physics Laboratory.

❑ In November 1998, NASA selected five new Discovery proposals for feasibility studies before making a final selection of one or two missions in June 1999. The five are **Aladdin**, a mission to gather samples from Mars' moons Phobos and Deimos; **Deep Impact**, which would fire a projectile into Comet P/Tempel 1 to expose its pristine interior ice and rock; **Inside Jupiter**, an orbiter that would study the giant planet's interior through measurements of its gravitational and magnetic fields; **Messenger**, an orbiter that would globally image and study Mercury; and **Vesper**, an orbiter that would study the atmosphere of Venus. In this round of selections, NASA also decided to fund part of an instrument to fly on the European Space Agency's Mars Express spacecraft in 2003 to study the interaction between the solar wind and Mars' atmosphere.

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 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.

Interstellar Dust

In 1990, NASA launched the Ulysses spacecraft on a flight path that would take it close to Jupiter, flinging it into an orbit around the Sun far above and below the ecliptic plane. 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 the similar dust detector on the Galileo spacecraft, which reached Jupiter in 1995.

Scientists believe that in fact 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 cycle of star formation and death, light elements such as hydrogen coalesce to form a 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.

Mission Overview

The Stardust mission will send a spacecraft looping three times around the Sun over the course of seven years. On the way it will collect interstellar dust on two different orbits, and 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 to the Utah desert carrying cometary and interstellar dust samples.

Launch

Stardust will be launched from Space Launch Complex 17A at Cape Canaveral Air Station, FL, on a variant of the Delta II launch vehicle known as a Delta 7426, one of the new series of launch vehicles procured under NASA's Med-Lite program.

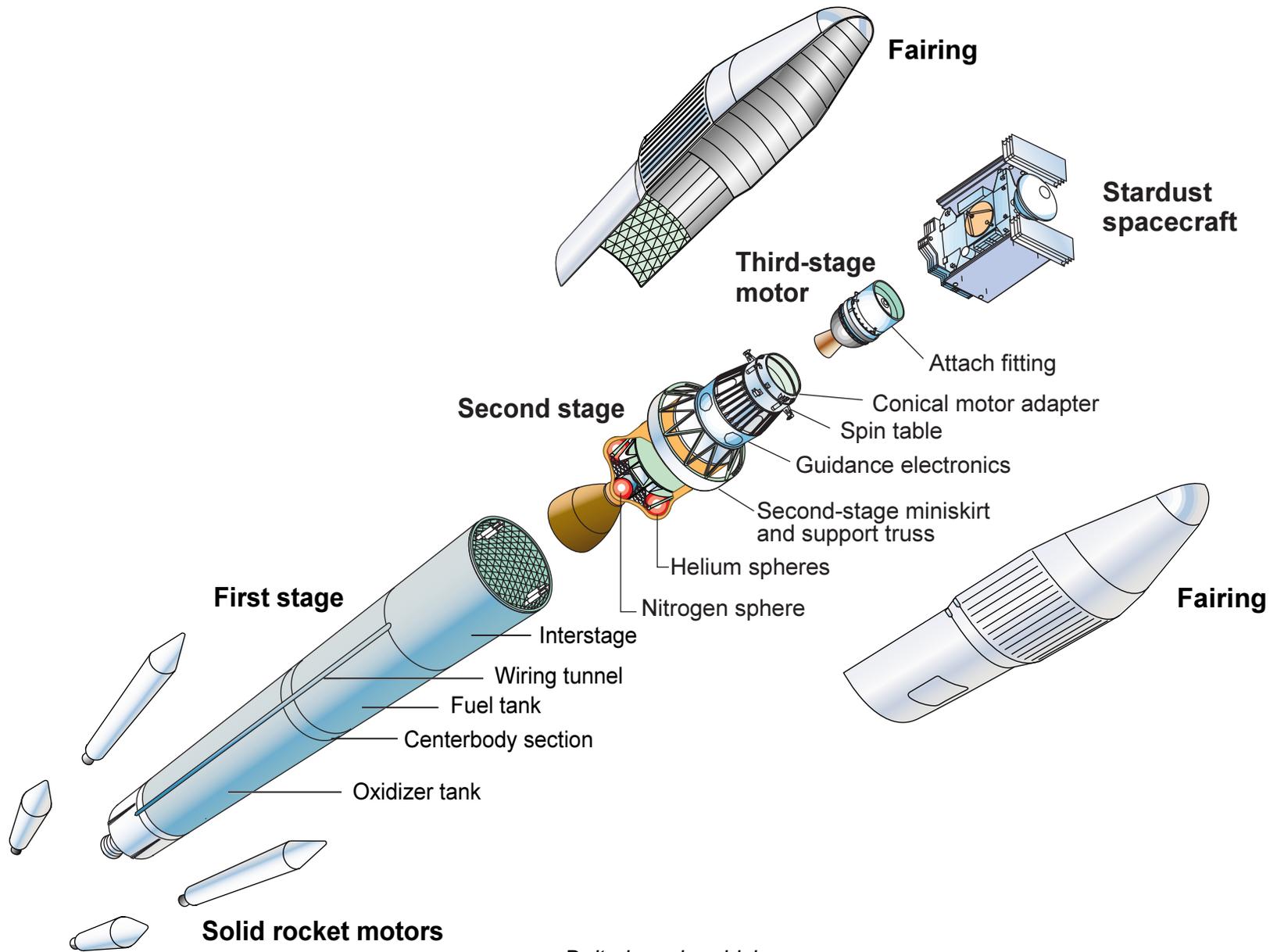
Launch vehicle. The first stage of the Delta II is augmented by four strap-on solid rocket motors. The solid rocket motors are designed to be jettisoned from the vehicle within 66 seconds after launch, after they have exhausted all of their solid propellant. Each of the four solid rocket motors is 1 meter (3.28 feet) in diameter and 13 meters (42.6 feet) long; each contains 11,765 kilograms (25,937 pounds) of hydroxyl-terminated polybutadiene (HTPB) propellant and provides an average thrust of 446,023 newtons (100,270 pounds) at sea level. The casings of the solid rocket motors are made of lightweight graphite epoxy.

The main body of the first stage is 2.4 meters (8 feet) in diameter and 26.1 meters (85.6 feet) long. It is powered by an RS-27A engine, which uses 96,160 kilograms (212,000 pounds) of RP-1 (rocket propellant 1, a highly refined kerosene) and liquid oxygen as its fuel and oxidizer.

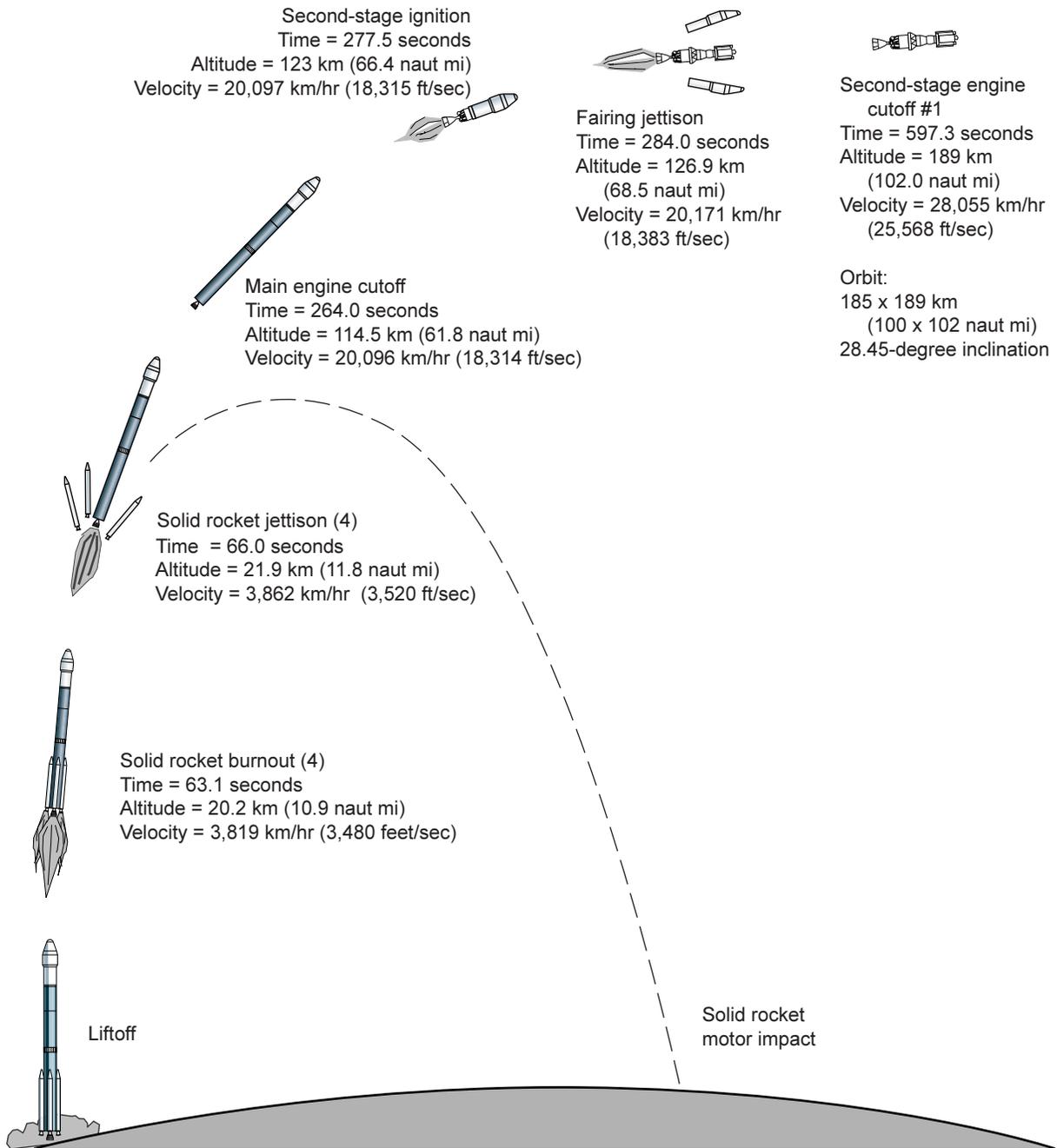
Daily Launch Opportunity

The spacecraft has one near-instantaneous launch opportunity each day (all times EST)

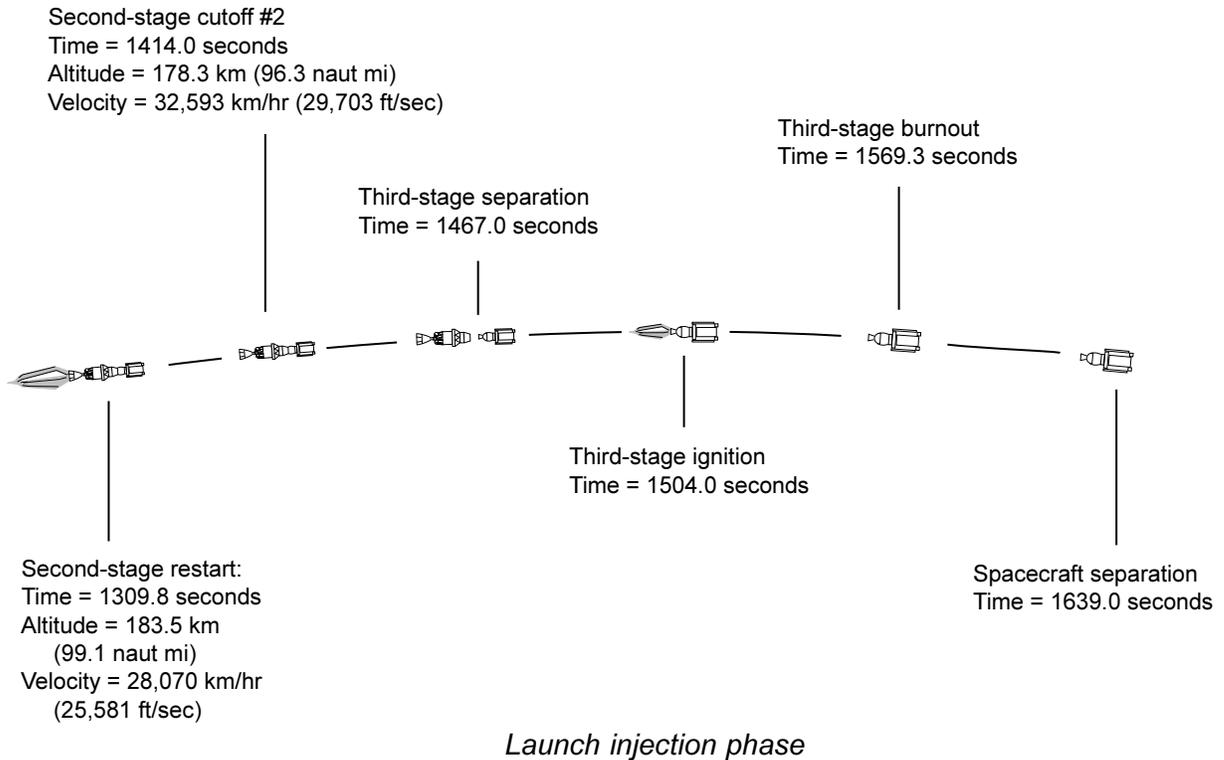
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2/8/99	4:00:26	2/18/99	2:04:32
2/9/99	4:18:03	2/19/99	2:27:44
2/10/99	4:19:15	2/20/99	2:29:09
2/11/99	4:20:51	2/21/99	2:30:47
2/12/99	4:19:15	2/22/99	2:32:33
2/13/99	4:20:03	2/23/99	2:34:26
2/14/99	2:01:16	2/24/99	2:42:45
2/15/99	2:01:42	2/25/99	2:44:50



Delta launch vehicle



Launch boost phase



The Delta II's second stage is 2.4 meters (8 feet) in diameter and 6 meters (19.7 feet) long, and is powered by an AJ10-118K engine. The propellant is 5,900 kilograms (13,000 pounds) of Aerozine 50 (A-50), a mixture of hydrazine and unsymmetrical dimethyl hydrazine (UDMH), with nitrogen tetroxide as the oxidizer. This engine is restartable, and will perform two separate burns during Stardust's launch.

The launch vehicle's third and final stage is a Thiokol Star 37FM booster, measuring 1.7 meter (5.5 feet) long and 0.9 meter (3 feet) wide. Its motor carries 1,090 kilograms (2,400 pounds) of solid propellant, composed of a mixture of aluminum, ammonium perchlorate and hydroxyl-terminated polybutadiene (HTPB). The third stage includes a spin table supporting small rockets which are used to spin up the third stage itself and the attached Stardust spacecraft. After Stardust separates from the third stage, a weight on a cable unwinds to tumble the third stage to avoid recontact.

Launch timing. The timing of Stardust's launch is based upon the trajectory the spacecraft must fly to rendezvous with Comet Wild-2 in 2004.

The launch period opens February 6 and continues through February 25, 1999. One near-instantaneous launch opportunity exists each day during the period. On February 6, the launch opportunity is at 4:07 p.m. Eastern Standard Time. The time of each daily opportunity varies (sometimes later or earlier) on later days of the launch period.

Launch events. Launch occurs in three phases, consisting of liftoff and insertion into a 189-kilometer (102-mile) parking orbit; a coast of about a half hour until the vehicle position is properly aligned relative to the direction it must leave Earth; and final injection to an escape trajectory. The total time needed to complete the process is a little under an hour.

Sixty-six seconds after liftoff, the four solid rocket motors will be discarded while the first stage continues to burn. About 4 minutes, 24 seconds after liftoff, the first stage will stop firing and be discarded eight seconds later. About five seconds later, the second stage engine ignites. The fairing or nose-cone enclosure of the launch vehicle will be discarded 4 minutes, 42 seconds after liftoff. The first burn of the rocket's second stage ends about 11 minutes, 22 seconds after liftoff.

About 21 minutes after launch, the second stage will restart. At about 24 minutes into the flight, the third stage will separate and burn for about two minutes, after which the Stardust spacecraft will separate from the third stage and begin its first orbit of the Sun.

Immediately after separation from the Delta's third stage, Stardust will stop its own spinning by firing its thrusters. About 4 minutes after separation, the spacecraft's solar array will be unfolded and be pointed toward the Sun. Shortly thereafter, the 34-meter-diameter (112-foot) antenna at the Deep Space Network complex in Canberra, Australia will acquire Stardust's signal.

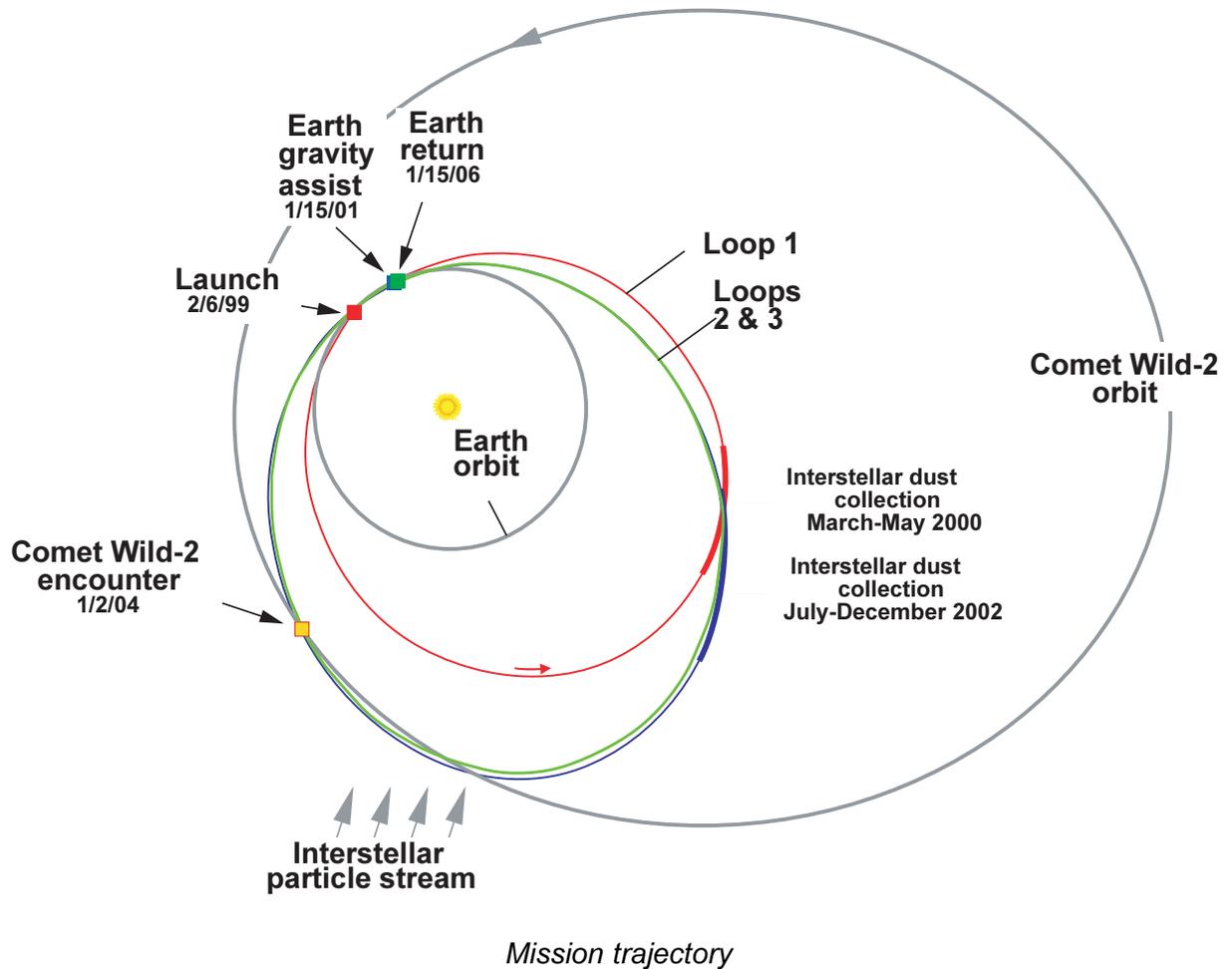
Cruise

Stardust's first two years of flight will take it on one orbital loop of the Sun. In March of 2000, when Stardust is between the orbits of Mars and Jupiter – the greatest distance that the spacecraft will be from the Sun – Stardust's onboard engines will fire to put the spacecraft on course for a later gravity assist swingby of Earth.

As Stardust travels back inward toward the Sun on the latter part of its first orbit, the spacecraft will pass through a region where interstellar particles flow through the solar system. From March through May 2000, the spacecraft will open a collector mechanism to capture such interstellar particles. The "B side" of the collector mechanism will be used, reserving the "A side" for the spacecraft's later dust collection mission at Comet Wild-2.

At the conclusion of its first orbit of the Sun, the spacecraft will fly past Earth on January 15, 2001 at an altitude of 5,964 kilometers (3,706 miles). This will increase the size of Stardust's flight path to a 2-1/2-year loop of the Sun. The spacecraft will stay this course through two more orbits.

As the spacecraft travels back inward toward the Sun on the latter part of its second orbit, it again will collect interstellar particles flowing through the solar system from July through December 2002.



Comet Flyby

One hundred and sixty days before encountering Wild-2 – or about July 25, 2003 – the spacecraft is scheduled to fire its thrusters to fine-tune its flight path through the comet's coma, based on updated information on the position of the comet's nucleus provided by the navigation camera. The encounter of Wild-2 will occur on January 2, 2004, when the comet is 1.86 astronomical units from the Sun (almost twice Earth's distance from the Sun) and 97 days after the comet has rounded the Sun.

At its closest approach, Stardust will be traveling at a speed of 6.1 kilometers per second (about 13,650 miles per hour) relative to the comet. The velocity has been chosen to optimize the capture of particles by the aerogel collector; at this speed, it can "soft-catch" the comet samples without changing them greatly. The passage through the most intensive rain of debris within the coma will last about eight minutes.

Wild-2 will be far from its peak period of activity and be relatively safe for a close flyby. The spacecraft will approach Wild-2 from above the comet's orbital plane, then dip slightly below it. In effect, the comet will "run over" the spacecraft. Approaching from the

sunlit side and northern portion of the comet, the spacecraft's flight path through the coma will take Stardust within about 150 kilometers (100 miles) of the comet's nucleus. This "miss distance" was selected to balance between the need to protect the spacecraft and the objective of sampling the freshest possible material off the comet's nucleus.

Stardust's navigation camera, which is fixed to the spacecraft body, will take images of the comet nucleus. The camera will be protected from direct hits because it faces away from the direction of the particle onslaught. It will record images of the comet through the reflection in a movable mirror. The mirror will provide image-motion compensation – that is, it will move to keep the reflection of the comet in the camera's field-of-view and minimize image smearing during the flyby.

Wild-2 is an ideal target in part because it has only recently been deflected from a distant orbit into its current orbit which brings it into the inner solar system. Its drastic orbit change resulted from a very close approach that the comet made to Jupiter in September 1974. Before that, the comet was in a much longer orbit and had made fewer passages of the Sun, so it is more pristine than most short-period comets. Since Comet Wild-2's orbit change in 1974, it has looped in toward the Sun three times. Comet scientists anticipate that 1 to 5 percent of Wild-2's nucleus surface could be active with gas and dust jets erupting from the surface. With a relatively slow flyby, the existence and activity of jets should be well observed.

Encounter Timeline

For planning purposes, the mission team has defined an encounter period spanning from 100 days before to 150 days after the comet flyby. This is divided into five time segments during which various mission activities are planned:

- Far Encounter** -100 days to -1 day
- Near Encounter** -1 day to -5 hours
- Close Encounter** -5 hours to +5 hours
- Closest Encounter** -240 seconds to +240 seconds
- Post Encounter** -0 days to +150 days

During the segment beginning 100 days before the comet encounter, the navigation camera will image Wild-2 weekly to assist in targeting the spacecraft. Stardust will repeatedly image the comet through the camera's eight different filters, acquiring as many images of the comet as can be practically returned until 12 hours before the closest approach to the nucleus. One closeup will be sent back to Earth near the point of closest approach. Subsequent imaging data will be recorded onboard the spacecraft for transmission to Earth after the fly-through of the coma has been completed.

The mission's core period for science data collection runs from about five hours before to five hours after its closest approach to the comet nucleus. Five hours and about 100,000 kilometers (60,000 miles) away from the nucleus, the spacecraft will begin to enter the coma. The comet's nucleus should begin to emerge in the navigation camera's field-of-view as an

extended dark body. All comet science experiments will be taking data, and the spacecraft will be tracked continuously throughout this period.

Just before the spacecraft's closest approach to the nucleus, Stardust will deploy its aerogel collector, with the "A side" facing the direction of incoming comet particles. The main Whipple shield, equipped with its dust flux monitor, will be counting particle hits. The comet and interstellar dust analyzer will be measuring comet particle composition during the fly-through. From -5 hours through -4 minutes, and again from +4 minutes to +5 hours, the spacecraft will transmit a continuous stream of imaging and other observations. At -4 minutes, when the comet nucleus occupies 60 by 60 picture elements (pixels) in the camera's field-of-view, a final black-and-white picture of the nucleus will be transmitted directly to Earth. Any images taken from -4 minutes to +4 minutes will be stored onboard for later transmission.

From -3 minutes to +4 minutes, one major goal will be to keep the comet nucleus within the camera's field-of-view. To accomplish this, the scanning mirror can adjust its position from viewing forward to backward, and the spacecraft itself can tilt to add a second axis to the mirror's position. This is expected to result in significant spacecraft motion, so mission planners expect to temporarily lose radio contact with Stardust. Should this loss of signal occur, Stardust's medium-gain antenna will take over communications functions until the dish-shaped high-gain antenna can be pointed again at Earth.

Once Stardust has completed its voyage through the coma, Stardust's aerogel collector will be stowed for the final time, sealing its comet and interstellar samples inside the sample return capsule. Imaging and other science data recorded onboard during the coma fly-through will be transmitted to Earth, and Stardust will begin the final leg of its journey back toward Earth.

Earth Return

Stardust is scheduled to fire its thrusters three times as it approaches Earth to fine-tune its flight path. The first trajectory maneuver is scheduled 13 days before Earth entry, the second three days before entry and the final maneuver 3 hours before entry. Earth entry will take place on January 15, 2006.

Soon after the final trajectory maneuver at an altitude of 110,728 kilometers (68,805 miles), Stardust will release the 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, light-weight thermal protection system. Additional ablative material on the back shell that is similar to material used on the Space Shuttle's external tank protects the capsule from the effects of recirculation flow of heat around the capsule.

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 with the 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 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. The capsule will be transported to a staging area at the Utah Test and Training Range where the sample canister will be extracted. The sample canister then will be transported to its final destination, the planetary material curatorial facility at NASA's Johnson Space Center, Houston, TX.

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 aerogel and any given particle is calculated to be at least 10,000 C (more than 18,000 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.

Outreach

The Stardust project has forged partnerships with several educational enterprises to increase public awareness of the mission's goals and strategy, and to broaden the distribution of new knowledge the mission will produce:

❑ **Challenger Center**, based in Alexandria, VA, has partnered with the project to manage the Stardust Educator Fellowship program. Twenty-five educators selected from across the country were trained in the science and engineering behind the mission. They also received a workshop package and educational materials, and will conduct their own teacher training on Stardust throughout the mission. More information about Challenger Center is available at its web site, <http://www.challenger.org/> .

❑ The **Jason Project**, founded by oceanographer and underwater explorer Dr. Robert Ballard after he found the wreckage of the Titanic on the sea floor, has created the "Jason IX Curriculum" in partnership with the Stardust project. The curriculum focuses on a study of life on Earth and in its oceans. The tie that links Stardust to oceanography is the presence of particles from space that lie on the ocean floor. Students will work with representatives of the Stardust mission to help find answers to the three key questions of the Jason Project: What are Earth's physical systems? How do these systems affect life on Earth? What technologies do we

use to study these systems, and why? The Jason Project's web site is at <http://www.jasonproject.org> .

❑ The Kirkpatrick Science and Air Space Museum, also known as **Omniplex**, is a hands-on science center located in Oklahoma City, OK. In partnership with the Stardust project, Omniplex has produced a planetarium show and a traveling "Stardust Cafe" exhibit dedicated to the science topics Stardust will investigate. The Omniplex web site is at <http://www.omniplex.org> .

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 1.136 million people are onboard the Stardust spacecraft.

The names were electronically etched onto fingernail-size silicon chips at JPL's Microdevices Lab. Writing 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 from October through November 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, DC, 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 Astronautics, Denver, CO. 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 are also 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 1933 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 return a few particles at the upper end of this size range, and a million particles in the submicron range.

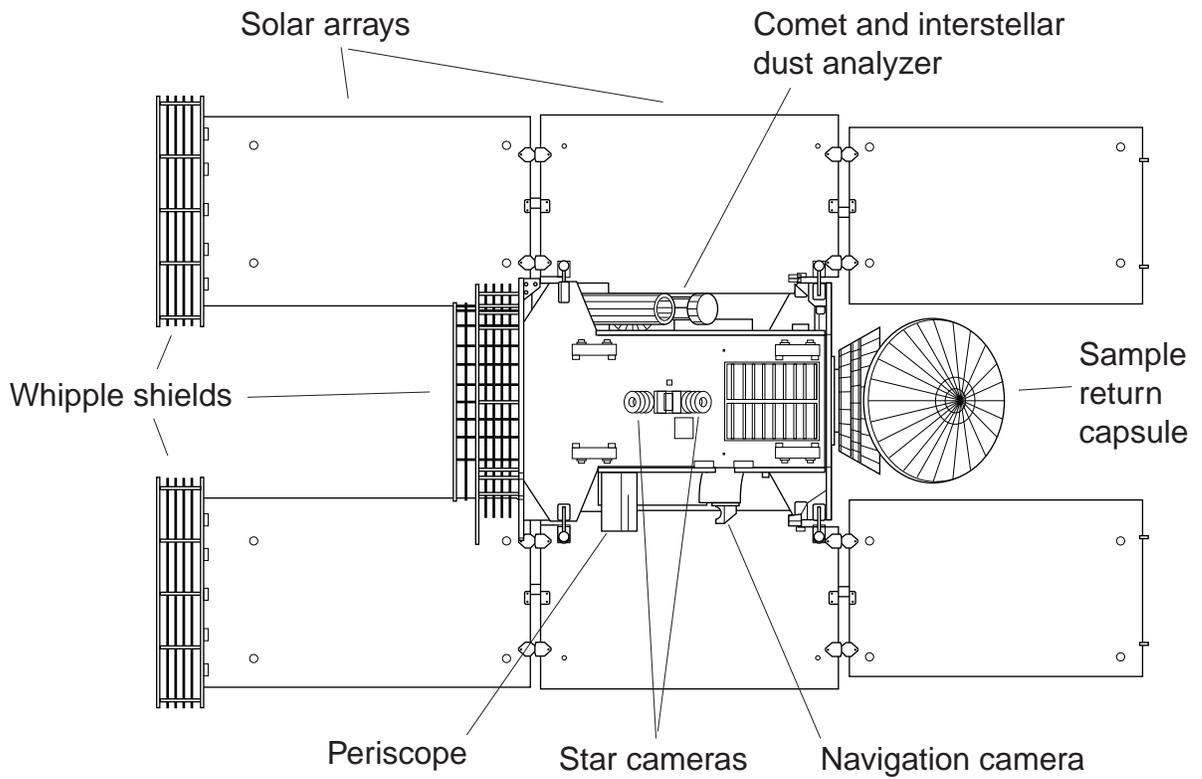
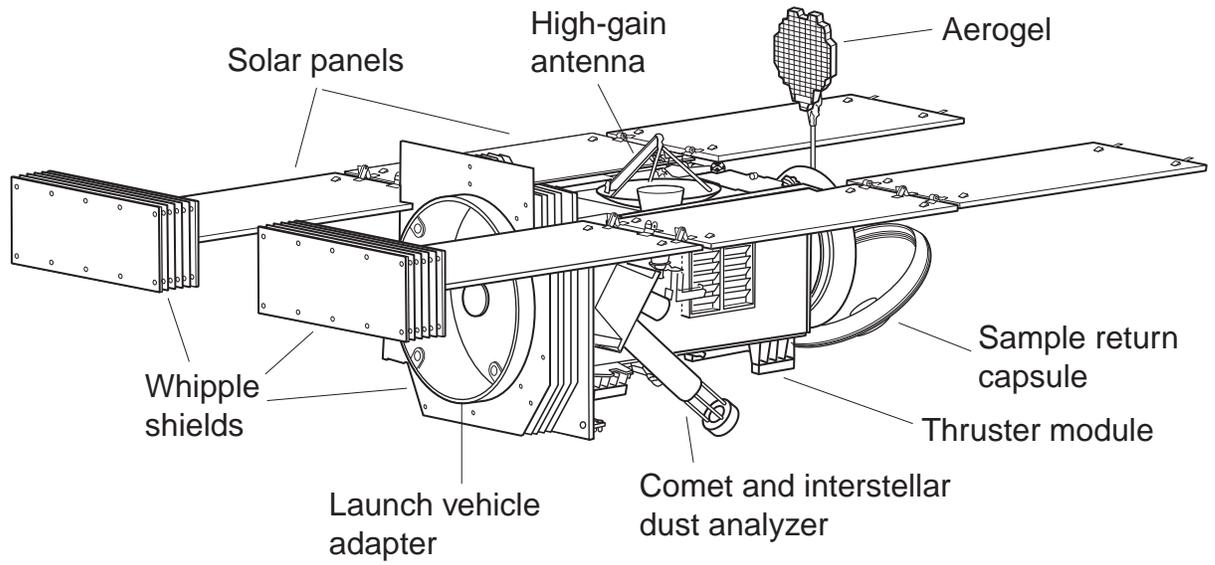
Most of the scientific analysis will be devoted to particles that are 15 microns (about 1/1,700th of an inch, or about one-third the width of a human hair) in size. The Stardust science team expects that the samples returned will be profoundly complex, and each particle will be probed for years in research 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. Stardust’s cometary and interstellar dust collectors each have 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.

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).



Stardust spacecraft

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. This material was developed by Lockheed Martin for use on the Viking missions to Mars in the 1970s, and is currently used on the Space Shuttle's external tank. The back shell 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 an 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 at an altitude of approximately 30 kilometers (100,000 feet) at a speed of about mach 1.4 to provide stability to the capsule. 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 an ultra-high-frequency (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 40 hours.

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 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 a 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 when 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 and constructed.

Navigation Camera

The navigation camera is capable of acquiring images with a resolution of 6 meters (21.6 feet) per pixel at a distance of 100 kilometers (62 miles).

The camera is a combination of adapted spare components left over from previous space 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 Voyager eight-position filter wheel, thermal housing, and spare optics and mechanisms. Designers added a thermal radiator to the Voyager camera. Combined with it 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.

The eight-position filter wheel is fitted with three gas filters, three dust filters, a high-resolution filter and a clear filter. The gas filters will permit study of the comet's dust jets as possible sources of gas, as well as a comparison of the sources of gas and dust on the surface of the comet nucleus. The three dust filters will allow study of the color and scattering properties of the dust. The high-resolution filter will be used for the highest-resolution imaging of the comet nucleus. The clear filter will be used for the study of structure and brightness differences on the comet nucleus.

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 is aided by a gravity-assisted boost maneuver when it flies by the Earth for the first time.

The spacecraft is equipped with two sets of thrusters which 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 for attitude control. The thrusters are in four clusters located on the opposite side of the spacecraft from the deployed aerogel. In all, the spacecraft carries 85 kilograms (187 pounds) of hydrazine propellant.

Attitude Control

The attitude control system manages the spacecraft's orientation in space. Like most planetary 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 other 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 are 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. Communications will be 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. Data rates will range from 40 to 4,000 bits per second.

A 0.6-meter-diameter (2-foot) high-gain dish antenna is used primarily for communication during the comet encounter. 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. 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 Nextel ceramic cloth that further dissipate and spread particle debris.

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 or differ.

During selected portions of its cruise phase, Stardust will collect 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 instruments provide unprecedented capabilities for analysis on the micron and submicron level, even to the atomic scale for imaging.

Stardust Science Team

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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 which are 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 AGB 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 car-

bonaceous 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, along with other evidence, has 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, CA is deputy principal investigator.

The Stardust mission is managed by the Jet Propulsion Laboratory for NASA's Office of Space Science, Washington, DC. At NASA Headquarters, Dr. Edward Weiler is associate administrator for space science. Dr. Carl Pilcher is science director for solar system exploration. Kenneth Ledbetter is director of the Mission and Payload Development Division, and Mark Dahl is Stardust program executive in the Mission and Payload Development Division. Dr. Thomas Morgan is Stardust program scientist.

At the Jet Propulsion Laboratory, Dr. Kenneth L. Atkins is project manager. Tom Duxbury is mission director. JPL is a division of the California Institute of Technology, Pasadena, CA.

At Lockheed Martin Astronautics, Denver, CO, Joseph M. Vellinga is the company's Stardust program manager, and Dr. Benton C. Clark is the company's Stardust program scientist. Lockheed Martin Astronautics designed, built and will operate the spacecraft, and will recover the sample return capsule.

1-29-99 JPL