continued from previous page

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

Spacecraft

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

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

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

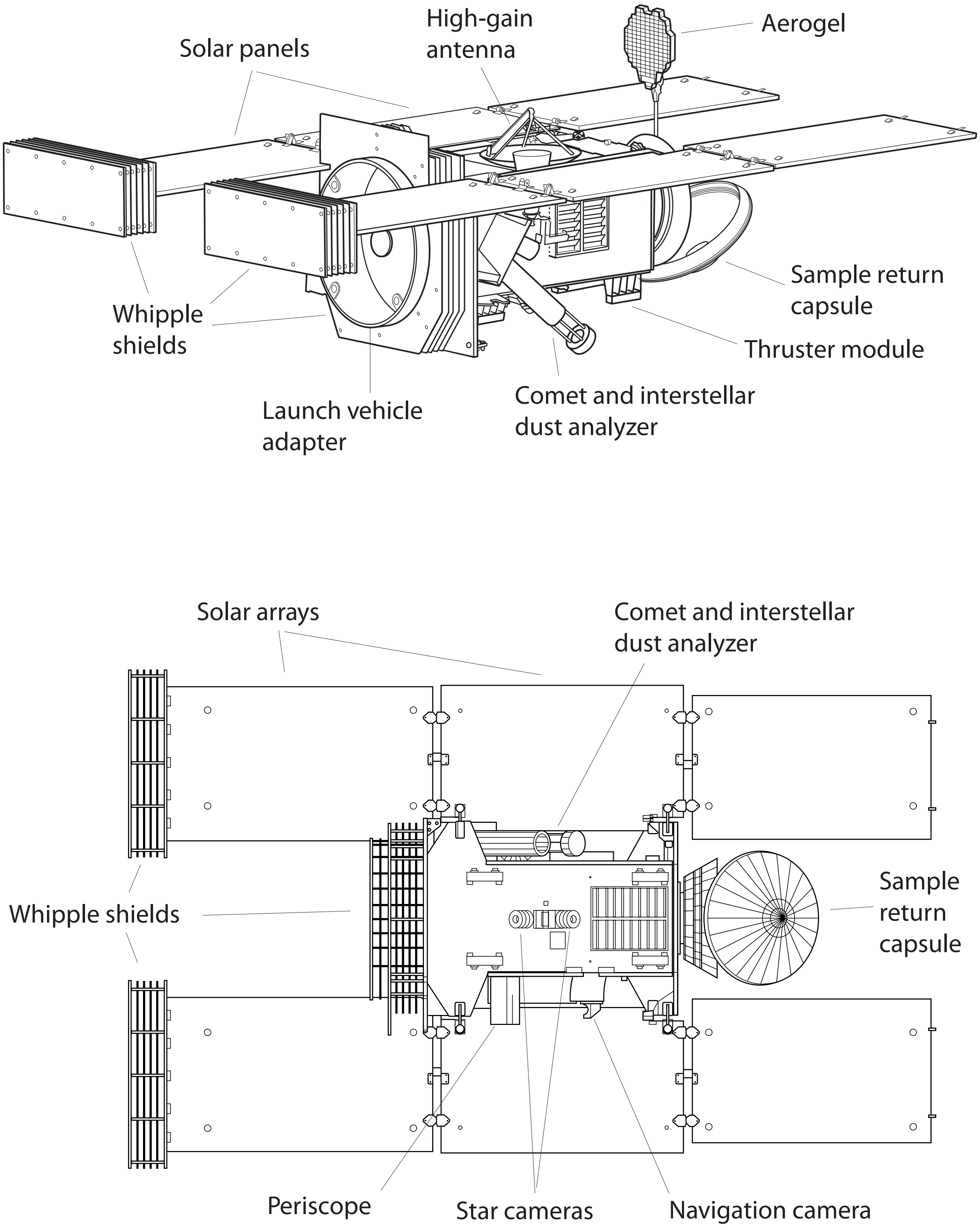
Aerogel Dust Collectors

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

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

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

Although the particles captured in aerogel are each smaller than a grain of sand, high-



Stardust spacecraft

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

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

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

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

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

Comet and Interstellar Dust Analyzer

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

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

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

Dust Flux Monitor

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

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

Navigation Camera

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

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

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

Propulsion System

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

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

Attitude Control

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

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

Command and Data Handling

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

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

Power

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

Thermal Control

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

Telecommunications

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

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

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

Redundancy

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

Whipple Shields

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

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

Sample Return Capsule

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

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

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

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

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

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

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

Science Objectives

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

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

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

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

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

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

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

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

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

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

Why Stardust?

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

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

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

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

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

Comets

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

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

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

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

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

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

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

Other Comet Missions

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

Other past and present cometary missions include:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Right Place, Right Time, Right Snowball

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

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

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

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

NASA's Discovery Program

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

Other missions in the Discovery Program are:

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

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

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

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

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

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

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

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

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

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

Interstellar Dust

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

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

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

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

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

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

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

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

Earth Assist

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

Program/Policy Management

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

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

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

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

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