Stardust: Comet and interstellar dust sample return mission

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Received 18 March 2003; revised 21 July 2003; accepted 19 August 2003; published 31 October 2003.

[1] Stardust, the 4th Discovery mission launched in February 1999, will collect coma samples from the recently deflected comet 81P/Wild 2 on 2 January 2004 and return them to Earth on 15 January 2006 for detailed laboratory analyses. Stardust will be the first mission to bring samples back to Earth from a known comet and also the first to bring back contemporary interstellar particles recently discovered. These samples should provide important insights into the nature and amount of dust released by comets, the roles of comets in planetary systems, clues to the importance of comets in producing dust in our zodiacal cloud as well as circumstellar dust around other stars, and the links between collected meteoritic samples with a known cometary body. Samples are collected in newly invented continuous gradient density silica aerogel. Stardust is facilitated by a magnificent trajectory designed to accomplish a complex and ambitious flyby sample return mission within the Discovery program restrictions. The remaining science payload, which provides important context for the captured samples, includes a time-of-flight spectrometer measuring the chemical and isotopic composition of dust grains; a polyvinylidene fluoride dust flux monitor determining dust flux profiles; a CCD camera for imaging Wild 2 coma and its nucleus; a shared X band transponder providing two-way Doppler shifts to estimate limits to Wild 2 mass and integrated dust fluence; and tracking of the spacecraft's attitude sensing for the detection of large particle impacts. The graphite composite spacecraft brings the collected sample back to Earth by a direct reentry in a capsule. *INDEX TERMS:* 1025 Geochemistry: Composition of the mantle; 1040 Geochemistry: Isotopic composition/chemistry; 3672 Mineralogy and Petrology: Planetary mineralogy and petrology (5410); 6015 Planetology: Comets and Small Bodies: Dust; 6210 Planetology: Solar System Objects: Comets; *KEYWORDS:* Stardust, Wild 2, interstellar dust, sample return, comet coma sample, silica aerogel

Citation: Brownlee, D. E., et al., Stardust: Comet and interstellar dust sample return mission, *J. Geophys. Res.*, *108*(E10), 8111, doi:10.1029/2003JE002087, 2003.

1. Introduction

[2] Stardust, the fourth NASA Discovery mission, launched on 7 February 1999, now circles the Sun in an orbit that will cause a close encounter on 2 January 2004 with the comet 81P/Wild 2. Stardust will collect coma dust at 150 km from Wild 2's nucleus and return it to Earth for detailed laboratory analysis on 15 January 2006. Figure 1 shows an artist's rendition of the Stardust spacecraft encountering the comet Wild 2 with the sample collector fully deployed. The Halley Intercept Mission (HIM) proposed in 1981 for the last comet Halley apparition inspired the near 2-decade quest for this comet coma sample return mission, Stardust.

[3] In addition, along the way to Wild 2, the backside of the Wild 2 sample collector will be used to capture interstellar particles (ISP) as bonus science. Besides the primary sample instrument, Stardust also makes in situ investigations to provide important context to the return samples: a time-of-flight spectrometer, a dust flux monitor, an optical navigation camera, an X band transponder for determining integrated dust flux and an estimate of the mass of Wild 2, and monitoring of spacecraft attitude control disturbances for large particle impacts.

[4] The return of lunar samples by the Apollo program provided the first opportunity to perform detailed laboratory studies of ancient solid materials from a known astronomical body. The highly detailed study of these samples revolutionized our understanding of the Moon and provided fundamental insights into the remarkable and violent pro-

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0148-0227/03/2003JE002087$09.00

Figure 1. Stardust at the Wild 2 encounter with the sample tray assembly fully deployed.

cesses that occur early in the history of moons and terrestrial planets. This type of space paleontology is not possible with astronomical and remote sensing. Despite these advantages, however, the last US sample return was made by Apollo 17 over 30 years ago! Now, 3 decades later, Stardust is leading a new era of sample return missions, including missions to return samples of solar wind [*Burnett et al.*, 2003], asteroid [*Fujiwara et al.*, 1999], and Mars [*Garvin*, 2002].

[5] For the last 3 decades, analysis of Interplanetary Dust Particles (IDP) and meteoritic samples has demonstrated that key information in these samples is retained at the submicron level. Unlocking the detailed records contained in the elemental, chemical, isotopic, and mineralogical composition of these tiny components can only be explored in detail with precise, flexible, state-of-the-art laboratory instrumentation. Laboratory analyses of samples can be repeated for consistency and verified by independent techniques and researchers. Having samples also permits the utilization of both current and future analysis techniques, new analysts, and ever improving instrumentation.

[6] Stardust scientists will perform a preliminary examination of the returned Wild 2 and interstellar samples [*Tsou et al.*, 2003]. After these preliminary examinations, the remaining samples will be remitted to the NASA Office of the Curator [*NASA*, 1994]. The NASA Office of Space Science will then issue a NASA Research Announcement (NRA) to invite proposals from the world sample analysis community.

1.1. Science Goals

[7] The science goals of the Stardust mission are prioritized into primary, secondary and tertiary objectives (P. Tsou, unpublished data, 1996) in order to provide a framework against which descopes could be taken when cost, schedule, or performance constraints were in jeopardy. Stardust has been able to fulfill all specified science objectives in the instruments, spacecraft, and mission implementations. The three prioritization categories for science objectives are as follows: (1) the primary objective is to collect 1000 analyzable particles of diameter >15 μm from Wild 2 and return them to Earth; the secondary objectives are to collect and return to Earth 100 contemporary ISP particles of diameter >0.1 μm, to obtain 65 images of the Wild 2 nucleus at resolutions of at least 67 μr/pixel as well as images of the Wild 2 coma, and to perform in situ compositional analysis of cometary particles within the coma; (3) the tertiary objectives are to perform in situ compositional analysis of interstellar grains, interplanetary dust and other cosmic particles, to collect Wild 2 coma volatiles, to determine Wild 2 coma dust flux and size distribution, to measure integrated dust fluence, large particle momentum and opportunistic estimate of the upper limit of the comet's mass, and to obtain dust flux profiles through Wild 2's coma.

[8] The Stardust science payloads meet these objectives through the use of a sample collector, a particle impact mass spectrometer, a dust impact detector, a camera, and shared spacecraft communication and attitude control subsystems.

1.2. Relationship to Other Cometary Missions

[9] Stardust is the first dedicated mission sponsored by NASA to encounter a comet, and the first to attempt to return captured material from that comet. Since NASA selected Stardust in 1995, four other NASA space missions targeting comets have been funded. Deep Space (DS) 1, a technology demonstration mission, carried out a successful flyby of comet P/Borrelly. The CONTOUR Discovery mission was to have conducted flybys to three comets: comet Encke, Schwassman-Wachman 3 and an unnamed

comet of opportunity but this mission failed at launch. Deep Impact, another Discovery mission, will send a projectile into comet Tempel 1. The fourth NASA cometary mission is the New Millennium program's Deep Space 4 technology demonstration mission to rendezvous with, orbit, and then land on comet Tempel 1.

[10] In addition to these NASA missions, ESA's Rosetta mission will rendezvous with another short period comet, Churyumov-Gerasimenko, study it for months from orbit with a large array of instruments, and then send a lander to the surface to perform in situ analyses of surface materials on the nucleus.

2. Scientific Significance

[11] The major current goal of sample return science is to determine the fundamental nature of comets at the submicron level, the size of initial nebular condensates and interstellar grains [*Brownlee et al.*, 1994a]. Stardust contributes to this scientific goal by bringing analyzable samples from both a "fresh" comet Wild 2 and contemporary ISP samples for detailed laboratory analyses. It will also acquire in situ time-of-flight mass spectra of solid particles, record the dust flux time series of Wild 2's inner coma, image the Wild 2 coma and nucleus and estimate the upperbound of the mass of the nucleus. The returned samples will constitute a resource that can be studied for years to come, compared with other types of meteoritic materials and remote astrophysical materials observed and studied by astronomical techniques.

[12] Although some meteoritic samples currently available in the laboratory are thought to be cometary, this is the first time primitive samples captured from a known comet will be made available for study. Thus the Stardust mission will return the first extraterrestrial samples from a known planetary body by a spacecraft since the Apollo and Luna moon flights and will provide direct contextual information for interpreting the properties of previously collected primitive meteoritic materials [*Brownlee et al.*, 1994a].

2.1. Comet Wild 2

[13] Wild 2 is a Jupiter-family comet that has only been in its present orbit since 1974. Prior to 1974, the comet orbited between a perihelion at 4.9 AU and aphelion at 25 AU; this orbit had been stable for at least several centuries [*Sekanina and Yeomans*, 1985; *Sekanina*, 2003]. In 1974 the comet had a close encounter with Jupiter which flung it into its current orbit, which has a perihelion distance of 1.58 AU and an aphelion near Jupiter's orbit at 5.2 AU. Thus Wild 2 is probably a relatively "fresh" comet whose outer layers have only recently been subjected to moderate solar heating. As a Jupiter family comet, samples from Wild 2 should be remnants from the Kuiper Belt region of the solar nebula. They are probably composed of submicron silicate and organic materials of both presolar and nebular origin.

[14] The comparison of Wild 2 samples (presumably sample solar system regions beyond Neptune) with meteorites (which sample the asteroid belt) will provide important insight into the materials, environments, and processes that occurred from the central regions to outer fringes of the solar nebula. The samples from Comet Wild 2, in conjunction with high-resolution images of the nucleus, will provide a means for accessing the diversity among comets when data from other comet missions become available.

[15] An exciting aspect of Stardust samples will be the synergistic linking of data from known cometary and interstellar dust samples with that of astronomical data of comets and circumstellar dust systems, and with data from laboratory measurements of meteorites and interplanetary dust samples collected in the stratosphere, Antarctica, and the ocean floor. The returned Stardust sample will be small in mass, but will provide critical context for these other materials and astronomical observations. For example, very simple properties of the Wild 2 samples may provide strong criteria for determining which interplanetary dust samples collected on Earth are similar or distinct from outer solar system cometary matter. A simple analogy would be the use of discovered properties of Apollo lunar samples to confidently identify rare meteorites with lunar origin.

2.1.1. Cometary Grains

[16] Both comets and asteroids are sources of IDP. The majority of IDP collected in the stratosphere is chondritic aggregates. Among these, anhydrous porous IDP are thought to be of cometary origin based on their porous structure, high carbon content, and high entry velocities [*Bradley and Brownlee*, 1986; *Sandford and Bradley*, 1989; *Thomas et al.*, 1993]. The Stardust sample will provide evidence for positive identification of cometary components in existing collections of meteoritic material, as well as comparison of inner and outer solar nebula processes, materials, and environments.

[17] Kuiper Belt comets formed at the outer fringe of the solar nebula where temperatures remained low enough during the formation of the solar system that intact interstellar grains should have survived normal nebular processing. At present, we do not know what fraction of cometary dust is interstellar and what fraction formed in the solar nebula. Similarly, we do not know whether material that condensed in the hot inner solar nebula was transported to the region of comet formation, or how these and other components might have been mixed and processed in the comet nucleus. Stardust will collect ancient interstellar grains incorporated into comets 4.5 billion years ago, and it will also collect contemporary interstellar grains currently passing through the solar system. This will provide a unique opportunity to compare samplings of interstellar material separated in both time and space.

[18] Bradley argues that a major structural submicron unit of the anhydrous IDP show evidence of heavy radiation processing that most likely occurred in the interstellar medium [*Bradley*, 1994]. These subunits, called GEMS (Glass with Embedded Metal and Sulfides), are an exotic material composed of silicate glass with large numbers of embedded 10-nm metallic and sulfide grains. GEMS have many properties that are consistent with astronomical observations of interstellar silicate grains. However, it has also been suggests that GEMS might have been formed by radiation processes within the solar nebula. If GEMS formed in the interstellar medium, then they should be abundant in Wild 2. There are actually many components of solar system materials that should have strong radial gradients in the solar system. Their presence and origins can be tested with the returned comet samples. In addition, it is not now clear whether meteoritic nanodiamonds and a

variety of rare gas and isotopic effects have nebular or presolar origins. If they have nebular origins, components such as nanodiamonds should be less abundant in Kuiper Belt comets than asteroidal meteorites because the comets formed an order of magnitude farther from the Sun and probably contain a higher abundance of interstellar materials.

2.1.2. Cometary Organics

[19] There is abundant evidence that comets are rich in organic materials. Organic compounds imported to Earth by comets may have played an important role in the formation of life on the early Earth [*Delsemme*, 1984]. Although Stardust is focused on nonvolatiles, the expectation is that a significant fraction of organic material will be contained in the captured samples. Stratospheric IDP commonly contain >10 wt% carbon. The in situ analysis of particles in the coma of Comet Halley by the precursors of Stardust's Cometary and Interstellar Dust Analyzer (CIDA) instrument showed that most of Halley's carbon and nitrogen is contained in solid ''refractory'' grains. These elements were seen both as organic rich ''CHON'' particles dominated by H, C, O and N as well as components finely mixed with silicates [*Clark et al.*, 1987; *Kissel and Krueger*, 1987].

[20] Thus the collected dust samples are expected to contain a significant fraction of organic material. Most of this material will reside in the grains and some organics will be collected as individual molecules on the collection surfaces. Examples of the types of organics that may be present include polycyclic aromatic hydrocarbons (PAHs), compounds similar to polyoxymethylene (POM), and aliphatic-rich kerogens [*Allamandola et al.*, 1987; *Schutte et al.*, 1993; *Bernstein et al.*, 1995].

2.2. Interstellar Samples

[21] Interstellar grains are the main repositories of condensable elements in the interstellar medium. Dust influences many types of astronomical observations and plays an important role in interstellar processes, including the formation of stars, planets, and comets. However, most of our knowledge of ISP is necessarily indirect. Spectacular work on meteorites has identified presolar grains in primitive meteorites, but this work has necessarily focused on exotic materials such as silicon carbide, graphite, and nanodiamonds, all nearly indestructible trace components that survived in the inner regions of the solar nebula where asteroids formed.

[22] The possibility of capturing contemporary ISP and returning them for detailed laboratory study on Earth is a relatively new possibility. In 1992, the dust instrument aboard the Ulysses mission identified the presence of micrometer-sized ISP grains passing through the solar system at 5.4 AU [*Grün et al.*, 1993]. Subsequent data from an identical dust instrument on board the Galileo spacecraft provided confirmation of the existence of these grains and helped establish their arrival direction and speed [*Grün et al.*, 1994].

[23] Stardust will capitalize on this new finding by collecting interstellar samples and making in situ measurements of their chemical and isotopic composition. This will provide ''ground truth'' for many astronomical observations and ISP models. Analysis of even a few captured contemporary ISP grains will profoundly influence our understanding of the interstellar medium and will be the key to a better interpretation of the existing telescopic data. These grains may prove to be an exciting target of opportunity and represent an important addition to the science of this mission.

3. Stardust Mission Development

[24] A traditional progression in solar system exploration starts with a flyby remote sensing mission, followed by an orbiter with remote sensing and in situ measurement, then a lander for in situ analysis and, finally, a lander with sample return. Comets offer a unique opportunity for combining an initial flyby mission with a sample return, since their comas represent fresh material ejected from their nuclei. Moreover, the cost of a flyby comet sample return mission is about an order of magnitude less than a lander sample return, making the realization of this quest within one life time more assured.

[25] However, in order to capitalize on this unique cometary coma sample return opportunity, intact capture technology of small particles at hypervelocities had to be invented and convincingly demonstrated. To achieve this, a three pronged parallel mission development strategy was conceived [*Tsou et al.*, 1988]: (1) invent and optimize intact capture technology to capture materials at as high a hypervelocity as possible; (2) develop a flight-qualifiedly flyby sample return instrument with a viable capture medium; and (3) gain broad science community support by submitting mission proposals and publications.

3.1. Enabling Technology Development

[26] The first proposed comet coma flyby sample return instrument was for the capture of material from comet Halley [*Tsou*, 1983]. Because of the high flyby velocities of 70 km/s resulting from Halley's retrograde orbit, only atomized sample return was proposed at that time. The work on atomized capture led to the more desirable goal of ''intact'' capture in which the impacting particle is not strongly heated or modified by the capture process. ''Intact'' collection refers to capturing particles at hypervelocities while retaining a significant analyzable portion of the particle that is both unmelted and retaining its original morphology. The first intact capture was achieved by capturing intact portion of a soft aluminum projectile in commercial styrofoam [*Tsou et al.*, 1984]. The laboratory successes [*Tsou*, 1990] were then validated by in situ space captures [*Tsou et al.*, 1993]. Further laboratory studies isolated specific factors that allowed for the capture efficiency to be improved since projectile size, particle integrity, and speed can be preselected. This allowed for the capture technologies to be improved more quickly than would have been possible if only space capture of particles were examined because particle sizes, composition, and speeds are random. The resulting intact capture technology that was developed and validated became the enabling technology for Stardust. After considering all pertinent factors [*Tsou*, 1995], ultra fine mesostructure silica aerogel with a bulk density as low as 2 mg/ml was chosen as the capture medium for Stardust.

3.2. Mission Development

[27] In 1984 a systematic all-sky search of comet coma sample return opportunities yielded few attractive comets

with low encounter speeds, <15 km/s, to permit intact capture (C. W. Yen, unpublished data, 1984). The search criteria also included low launch energy (to avoid expensive launch vehicles), moderate delta V (to minimize large trajectory maneuver requiring large amounts of propulsion fuel), and a comet for which there was some trajectory history and a known dust production. Thus it was remarkable that a magnificent trajectory that reduced the encounter speed to as low as 5.4 km/s to a "fresh" dusty comet was conceived for Stardust [*Tsou et al.*, 1994; *Yen and Hirst*, 1997]. It is significant that all four imperatives are met in this Stardust trajectory: a dusty comet with centuries of history, a remarkable low comet encounter speed, launchable by Delta II vehicle, and small delta v. Even more remarkable is that the encounter speed is well within the capability of most two-stage light-gas guns so that the sample collector and dust shield designs can be validated.

[28] The first comet coma sample return proposal was an augmentation to the HIM (Jet Propulsion Laboratory, unpublished data, 1981) with an atomized sample return, which evolved into a dedicated HER (Halley Earth Return) mission carrying only a sample collector [*Tsou*, 1983] and a camera, as shown in Figure 2. This was followed by a Comet Intercept Sample Return Mission proposed to NASA's Planetary Observers program in 1985. Lacking success, Giotto II, a joint NASA/ESA Mission making use of the backup Giotto spacecraft for a comet coma sample return mission, was proposed (A. L. Albee, unpublished data, 1985). Giotto II then inspired CESAR, Comet Earth Sample and Return, an all-European comet coma sample return mission (J. A. M. McDonnell et al., unpublished data, 1996). Then the quest went East to the Institute of Space and Astronautical Science (ISAS) of Japan for the joint NASA/ISAS SOCCER Mission, Sample Of Comet Coma Earth Return [*Shimizu et al.*, 1991; *Albee*, 1992]. The cancellation of the Comet Rendezvous and Asteroid Flyby Mission (CRAF) in 1992 resulted in the shifting of Rosetta from nucleus sample return to CRAF-like objectives in 1993, and the choice of the ISAS for Hayabusa (previously Muses C) rather than SOCCER were some of the other pivotal programmatic developments that facilitated Stardust turning from an interstellar-focused Discovery sample return mission to a comet-coma-focused sample return mission.

3.3. Discovery Programmatic Constraints

[29] The NASA Discovery AO [*NASA*, 1994] was the first openly competed mission opportunity under the new "faster, better, cheaper" mantra. This placed several new constraints on this mission, such as launch vehicle class, latest time of launch, cost cap, and required industry teaming arrangements. These constraints, along with an understood need to reduce mission risk by avoiding dependence on the Space Shuttle for sample recovery service [*Albee et al.*, 1993], shaped the design of the Stardust mission and the design of its sample return instrument. Without a Shuttle Earth return option, direct Earth reentry by a capsule was dictated. The AO specified class of "Med-Lite" launch vehicle limited the type of mission (i.e., no rendezvous) and the maximum spacecraft mass (400 kg) that could be delivered to a Wild 2 intercept trajectory with low encounter speed. Achieving the necessary intercept trajectory required a C3 of 26 km^2/s^2. A magnificent three-orbit flyby sample return trajectory was conceived that neatly fitted within these constraints.

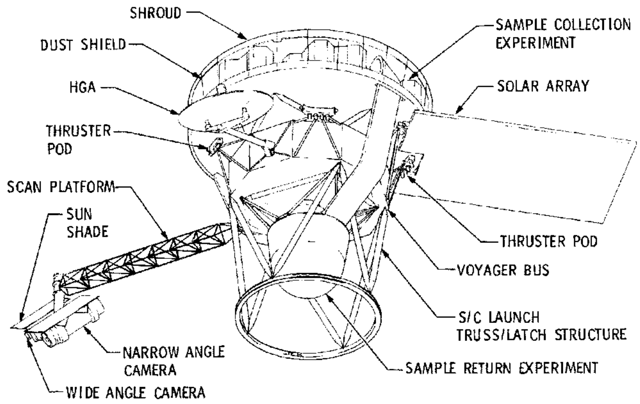

Figure 2. Halley Earth Return mission spacecraft with only two payloads: an atomized sample collector instrument, which also served as the spacecraft dust shield, and two imaging cameras.

3.4. Primary Instrument Development

[30] This intact capture technology must be implemented into realistic flight qualified sample collection instrument that satisfies all space flight qualifications and requirements. Ultraviolet radiation and temperature extremes are ubiquitous in space, and some of the polymer foams proven effective for intact capture in the laboratory would not survive long under these space conditions. The opacity of polymer foams also made it difficult to find and analyze captured particles. In spite of lower intact capture efficiency, silica aerogel was adapted as the optimum capture medium for space flight due to its many outstanding space compatibility properties and acceptable capture efficiency [*Tsou*, 1995]. Extensive space flights of aerogel gained both experience and confidence in handling aerogel and expedited the space qualification of aerogel for the Stardust Wild 2 and Interstellar Sample Collection and Earth Return (WISCER) instrument [*Tsou et al.*, 2003].

3.5. Heritage of In Situ Instrument

[31] The Comet and Interstellar Dust Analyzer (CIDA) [*Kissel et al.*, 2003], a time-of-flight mass spectrometer, is an enhanced version of the PUMA and PIA instruments successfully flown on the Vega and Giotto Halley missions [*Kissel et al.*, 1986]. The Dust Flux Monitor investigation [*Tuzzolino et al.*, 2003] is a polyvinylidene fluoride particle penetration dust flux monitor. The engineering Optical Navigation Camera (NavCam) [*Newburn et al.*, 2003a] is a Voyager purchased camera [*Jet Propulsion Laboratory*, 1987] with videcon replaced by a Cassini CCD and modified Clementine digital electronics.

4. Overview of the Stardust Mission

[32] Besides the technology breakthroughs in sample collection, the Stardust 7-year trajectory was another significant achievement [*Yen*, 1997]. The sample collection of Wild 2 will be accomplished within an 1800 km track

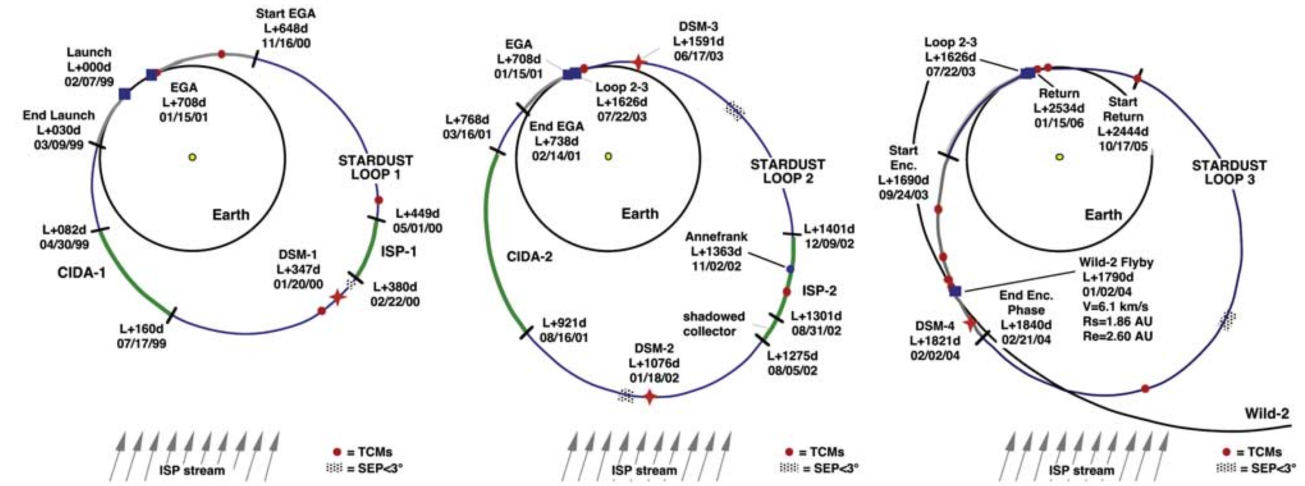

Figure 3. Stardust three-loop trajectory, with markings showing the portions of the orbits for each cruise science (CIDA-1, -2, and -3, ISP-1 and -2), the planned deep space maneuvers (DSM number) and major mission events as launch, Earth Gravity Assist, Annefrank, and Earth return, with the time of each event indicated by launch (L) + days from launch and the calendar time.

centered at the Wild 2 closest encounter on 2 January 2004. To arrive at this 5 min period, the Stardust spacecraft will have to travel 5 years. It will take 2 more years to return the captured samples to Earth. During the long 7-year Stardust cruise phase, the secondary and tertiary science objectives fulfilled along with an Earth Gravity Assist on 15 January 2001, followed by the Annefrank asteroid encounter on 2 November 2002.

4.1. Stardust Trajectory

[33] This magnificent trajectory enabled the very ambitious two sample return missions (Wild 2 and ISP) while still meeting the low-cost Discovery program requirements. Significant features of this trajectory include: (1) finding an excellent, recently deflected, fresh and dusty comet, Wild 2, as the target; (2) utilizing an Earth-gravity-assist maneuver to compensate for limited launch vehicle performance; (3) achieving a significant reduction in sample encounter speed to 5.4–6.1 km/s, thereby ensuring intact capture of samples; (4) designing a trajectory needing a very low total delta-V (355 m/s) resulting in a simple monopropellant hydrazine propulsion system requiring only a modest amount of fuel; (5) providing a very modest Earth return speed (12.6 km/s) for a deep space returning vehicle permit a modest direct reentry vehicle design; (6) meeting the Discovery AO requirement for a launch before 15 August 2001; (7) finding a trajectory such that during the encounter the direction to the Earth is 90° to the flyby direction, thus allowing a fixed high-gain antenna, and communications during the flyby while maintaining the spacecraft behind the dust shields; and (8) accomplishing the entire Stardust mission in an acceptable mission duration of 7 years.

[34] The Stardust three-loop orbit trajectories are shown in Figure 3. The trajectory began with an escape from Earth on 7 February 1999 on a three-stage Delta 7426 launch vehicle. During the 7-year mission, the spacecraft makes three heliocentric revolutions, all with perihelia at 1.0 AU. After the first revolution, the spacecraft performed an Earth Gravity Assist at 6,008 km altitude above Earth. This maneuver raised Stardust's orbital aphelion to 2.7 AU and changed the orbital inclination to 3.6° deg with respect to the ecliptic plane to better match that of Wild 2's orbit. The Wild 2 encounter will occur on 2 January 2004, about a third way into the third heliocentric revolution. For the return journey, the Earth intercept will take place at the end of this third heliocentric revolution on 15 January 2006.

[35] The second orbit has also taken the Stardust spacecraft to its furthest distance from the Sun, 2.72 AU. This represents the current distance record for a solar powered spacecraft. This also presented a challenge due to the shortage of electric power at aphelion needed to keep spacecraft critical hardware subsystems warm and within operating ranges.

4.2. Mission Phases

[36] The Stardust science mission can be grouped chronologically into the following phases: (1) ground preparation, the installation and testing of all instruments; (2) launch, no instrument in operation; (3) cruise 1, ISP composition, IDP flux, ISP collection, occultations; (4) Earth Gravity Assist, imaging the moon; (5) cruise 2, Annefrank flyby, repeat cruise 1; (6) Wild 2 encounter, all instruments and shared engineering science on; (7) cruise 3, quiet with no planned science operation; (8) Earth return, no science instrument, sample capsule release; (9) capsule recovery, deintergrate sample recovery subsystem; and (10) preliminary examination, sample documentation, analyzing selected samples.

[37] A summary of the Stardust mission design overview for the full 7 years is shown in Figure 4. Mission phases, science, and mission events are indicated in the left column. All flight instruments and spacecraft subsystems met all flight hardware reviews at Preliminary Design Review and Critical Design Review and preparations needed for launch. All the science instruments were assembled to the spacecraft at the LMA facility at Littleton, Colorado and qualified as a system. Instruments having direct flight inheritance did not require their own individual hardware reviews but partici-

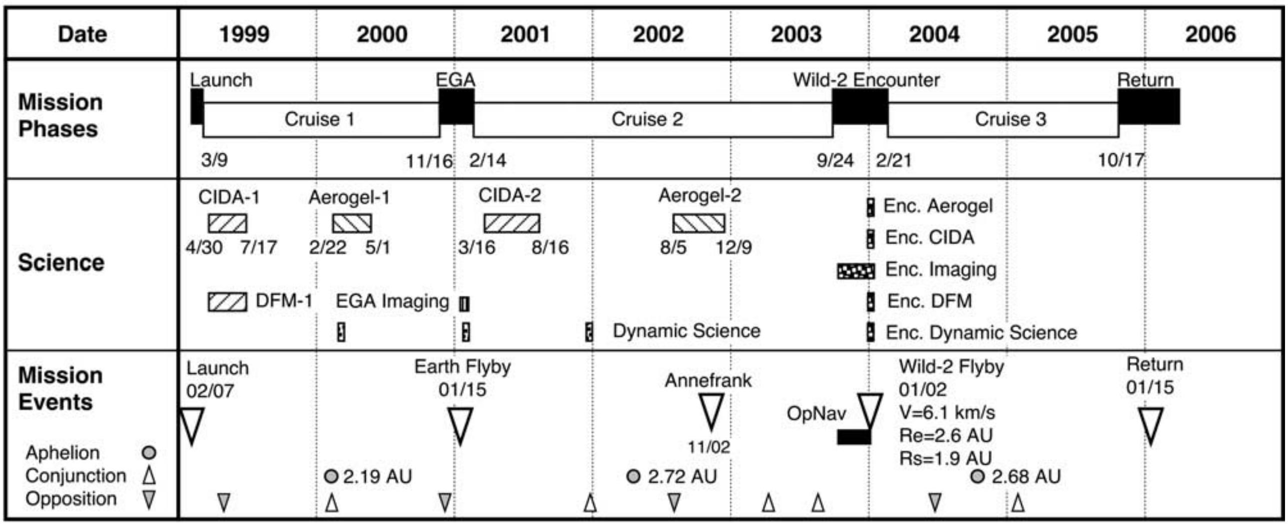

Figure 4. Stardust mission overview, with the number of days from launch indicated at the bottom of the mission phases; the time of operation and planned duration of each investigation are indicated in science; the major mission events are indicated by large triangles, with the time and distance of spacecraft aphelions and the time of solar conjunctions and oppositions indicated.

pated in the overall Stardust Assembly Test Launch Operations activities.

4.3. Launch

[38] The spacecraft was delivered to the Kennedy Space Center to be integrated with the Delta II launch vehicle in November 1998. The launch period was 20 days and the launch window for each day was instantaneous. Stardust's initial orbital injection was so accurate that it did not have to perform the first scheduled trajectory correction maneuver to correct launch error. The optimal launch date was 6 February 1999, but due to a technicality the first launch attempt was scrubbed. On the next day Stardust was launched successfully at 0932 UT from the Pad 17A Cape Canaveral Air Station.

4.4. Cruise

[39] During the inbound portions of the heliocentric orbits, the trajectory of the Stardust spacecraft parallels that of the ISP steam passing through the solar system. This results in a reduced relative speed between the spacecraft and the ISP enhancing the intact capture of ISP. During the first two orbits, the Stardust collector was deployed for a total of 246 days to capture ISP on the back side of the sample tray assembly.

[40] The CIDA instrument was powered on soon after launch to make the first of two measurements of interstellar particles at the beginning of each of the outbound legs of the first two Stardust orbits. On the outbound portion of the orbit, the speed of the spacecraft is added to the interstellar stream speed to enhance the impact ion generation for the sparser and smaller ISP.

4.5. Wild 2 Encounter

[41] At the beginning of the third orbit, the spacecraft will already be on a trajectory that will intercept Wild 2. At encounter, the comet overtakes the spacecraft. Beginning some 90 days prior to the Wild 2 encounter, the NavCam will take optical navigation images, which will provide refinement for the closing trajectory. The Stardust spacecraft will be targeted for a nominal closest approach distance of 150 km to the Wild 2 nucleus. This encounter distance can be varied within limits depending upon updates from the coma dust model and the NavCam observations. At the time of encounter, 1.86 AU from the Sun, Wild 2 will be 98.8 days past its perihelion. The sample tray assembly (STA) of WISCER will be extended for the third and final time 9 days before the encounter. CIDA would have been on for some time. The dust flux investigation will be turned on for 30 min about the closest encounter. The last trajectory maneuver will be performed 18 hours before the closest Wild 2 approach to finalize the encounter distance; a contingency maneuver is planned at 6 hours before encounter to account for any late breaking changes to the Wild 2 dust environment. As the Wild 2 nucleus comes into view, images from the NavCam and an onboard, closed-loop tracking algorithm, will determine the amount of the spacecraft rotation about the *x* axis necessary to keep the Wild 2 nucleus in the field of view of the NavCam. At 5 min before the closest encounter, the spacecraft will execute a bank turn, if any. A carrier-only signal will be maintained by using the spacecraft's medium gain antenna. The 5 min surrounding the closest approach will be the culmination of Stardust's 7-year journey, with every instrument operating in the highest data rate and experiencing the highest dust flux rendering the spacecraft a speeding plasma ball.

[42] Three min after the closest encounter, the spacecraft will reverse the bank turn and lock on Earth through the high-gain antenna to transmit the data stored during this period. Promptly, after assessing the status of the WISCER from the engineering indicators, the sample tray assembly (STA) will be retracted and the clamshell of the Sample Return Capsule (SRC) locked ready for Earth return.

4.6. Earth Return

[43] The spacecraft will reach Earth for a nighttime landing at the Utah Test and Training Range (UTTR) on

15 January 2006, after traveling a total distance of nearly 4.5×10^9 km. At 4 hours before Earth entry, the SRC will be spun up for stabilization and released from the spacecraft. Earth reentry will occur at 0957 UT followed by parachute deployment and descent of the SRC to the ground. Unless weather hazards preclude it, a joint crew of the Stardust Preliminary Examination Team (PET), the UTTR Recovery Team, and the LMA Operations Recovery Team will recover the SRC immediately by helicopter. A gas sample from the sample canister will be taken, then the capsule will be placed in an environmentally controlled container, and then will be flown to Hill Air Force Base, Utah, for another flight to Ellington Air Force Base, Texas, and then transferred to the NASA curatorial facility at Johnson Space Center. The Stardust PET will document all of the sample recovery process and perform a preliminary examination of the returned samples.

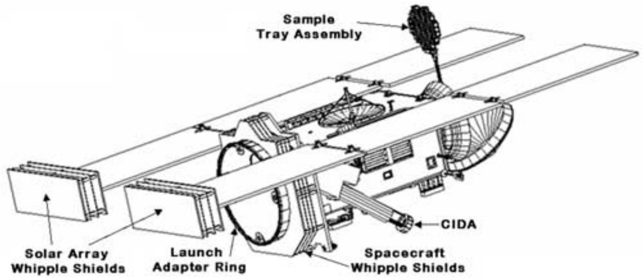

Figure 5. Stardust spacecraft at Wild 2 encounter, viewing from Wild 2. Two solar panel dust shields and a spacecraft bus dust shield are in the forefront. On the main dust shield a portion of the launch adapter ring remains. The Cometary and Interstellar Dust Analyzer is mounted on the side, with the impact surface protruding beyond the main dust shield.

5. Flight Engineering Hardware

[44] Stardust was proposed and managed by the Jet Propulsion Laboratory (JPL) but the flight hardware was built by an industrial partner. The Stardust flight hardware consists of two major components: the spacecraft and the SRC which houses the WISCER. At the time of the Stardust proposal, Martin Marietta Aerospace in Denver was selected as the industrial partner. After Stardust selection, Martin Marietta Aerospace was merged with the Lockheed Aircraft Company and became Lockheed Martin Astronautics (LMA).

[45] The Stardust spacecraft utilized the SpaceProbe deep-space bus developed at LMA. The SRC is derived from the Viking capsule and more recent studies performed under Mars Sample Return prior to Stardust by LMA.

5.1. Spacecraft

[46] The Stardust spacecraft, as viewed from Wild 2 during encounter, is depicted in Figure 5. The spacecraft bus is predominantly made with flat panels fabricated with thin sheets of graphite fibers in polycyanate resin covered over lightweight aluminum honeycomb core. Six panels form a rectangular box of nominal dimension 1.6 m length and a square cross section of 0.66 m on each side. During encounter, the smallest cross-sectional end of the spacecraft is oriented into the direction of the velocity in order to minimize the area which must be shielded from hypervelocity dust impacts as the spacecraft traverses through the Wild 2 coma.

5.1.1. Dust Shields

[47] Wild 2 coma dust is the object of the primary Stardust science, but at 6.12 km/s, these hypervelocity particles will damage the spacecraft. Thus a distinguishing feature of the Stardust spacecraft is the multilayer dust shields placed in front of the spacecraft bus and two solar arrays as shown in Figure 5. These “Whipple shields” consist of a front composite panel bumper shield, followed by three equally spaced layers of Nextel ceramic cloth, and a composite panel as the catcher shield in the back which also forms the structural end of the spacecraft bus. The solar arrays are feathered into the coma particle flux, but wider dust shields are needed to compensate for imperfect alignments and the fact that there is some dispersion in apparent particle flux angle due to size-dependent cometary dust ejection velocities from the nucleus. The Whipple shields protecting the solar arrays are similar to that for the main body, but the final design made use of two Nextel ceramic cloth blankets instead of three.

5.1.2. Articulations

[48] Owing to the Discovery program cost constraints and the long flight time, spacecraft simplicity and robustness have been central consideration in the design. Thus no gimbals are used on the Stardust spacecraft – all antennae and the solar arrays are body mounted (fully deployed in its final configuration 4 min after spacecraft separation from the launch vehicle). The only articulations needed for the entire mission are those associated with (1) deploying the STA out of the SRC to extend beyond the high-gain antenna and the main spacecraft Whipple Shield, and (2) the NavCam scanning mirror for tracking the Wild 2 nucleus. Except for the spacecraft battery, most subsystems are fully redundant.

5.1.3. Attitude Control

[49] Attitude control of the spacecraft is maintained through the use of 8 small thrusters of 0.9 N thrust each and an additional 8 larger thrusters, 4.4 N, for trajectory correction maneuvers and for major reorientations should it be necessary due to a large particle hit during passage through the coma. All thrusters are mounted on the lower panel of the spacecraft in groups of four, away from the STA. Figure 6 shows the underside of the spacecraft and the four thruster pods. A special grade of ultrapure hydrazine, the same as was used to prevent Viking landers from contaminating the Martian surface, is used due to intrinsically clean-burning and organic-free monopropellant. Following launch, the spacecraft was despun and adopted 3-axis attitude control. During the long periods of cruise, the star camera provided attitude sensing. During the comet encounter, the gyroscopic inertial measurement unit will be activated along with the attitude control dead band decreased to less than 0.2° in order to maintain the Whipple shields within the ±2° uncertainty to protect the spacecraft and the solar array panels.

5.1.4. Communication

[50] The telecommunications system uses the X band transponder design from the Cassini mission. 15 W of radio frequency power feeds a low gain antenna, medium gain horn and a 0.6 m diameter high-gain dish antenna, shown in

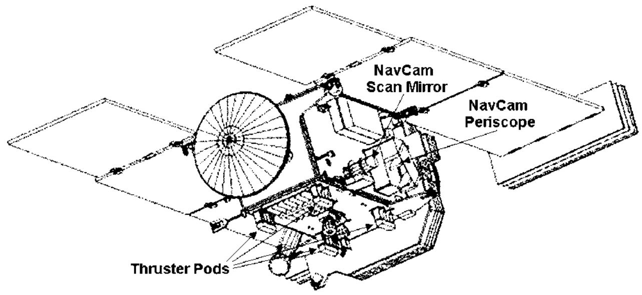

Figure 6. The four thruster pods are mounted on the opposite side of the sample tray assembly to avoid contamination of the collected samples. The scan mirror and the periscope of the Optical Navigation Camera is mounted behind the main Whipple shield with a slot for the periscope. The periscope provides protection during the Wild 2 approach for the scan mirror from dust impacts.

Figure 7. At the time of encounter, the data rate is expected to be no less than 7.9 kilobits/s through the 70 m antennas of the Deep Space Network. At the closest Wild 2 approach, much higher resolution images will also be acquired, but not downlinked in real time since the spacecraft may have to execute a bank turn and miss Earth in the field of view of the high-gain antenna. All imaging and other instrument data will be stored in the on-board 1.02 gigabit RAM memory for later playback.

5.1.5. Processor

[51] Being highly integrated, a combined command and data handling unit incorporates a RAD6000 central processor, mass memory, and associated input and output channels. The RAD6000 operates at 5, 10, or 20 MHz clock rates and hosts the software that will be used real-time control of the NavCam scan mirror and spacecraft bank turn adaptively as Stardust passes the Wild 2 nucleus at closest encounter.

5.1.6. Power

[52] To enable Stardust to go farther into deep space than any previous solar-powered spacecraft, a combination of features were used including low-power consumption subsystems, power switching, carefully tailored thermal control, specially selected solar cells with enhanced low-intensity low-temperature performance, and in flight solar cell reconfiguration capability. This latter capability assists with handling the large solar distance variations and maximizing performance during critical power periods, such as aphelion passages and Wild 2 encounter.

5.2. Sample Return Capsule

[53] The SRC, shown in Figure 8, houses the WISCER and is a blunt-nosed vehicle of 60° half-angle. It utilizes two types of thermal protection material for the reentry heating environment. The forward heat shield is a special phenolic impregnated carbon ablator, newly development by the NASA/Ames Research Center. The aft body ablator is the super lightweight ablator SLA-561, originally developed by Martin Marietta Astronautics for Viking lander entry heat shields and the nose portion of the Shuttle's External Tank. The STA is protected inside an aluminum canister housing, which is sealed by a Teflon U-ring and vented through a custom-designed filter to reduce the ablative shield's pyrolyzed products during reentry. To achieve stability during all phases of reentry and descent, the SRC has a carefully controlled center of mass location, is spun up to 16 revolutions per min when released to maintain aerodynamic stability, and deploys both a drogue and main parachute upon reaching the lower atmosphere. The WISCER instrument is a designated science portion of the sample subsystem and refers primarily to the STA. The Sample Canister (SC) is a near-circular, all-aluminum honeycomb base plate with bare aluminum face sheets. Upon this surface are anchored the STA and other mechanisms including the SRC avionics, along with all electromechanical devices needed to open the capsule's clam-like cover, deploy the STA, stow the assembly, and close and lock the clamshell cover. The SC has a near-circular aluminum cover. The STA consists of two bare aluminum trays mounted back to back in a single assembly: a 3-cm-thick Wild 2 sample tray and a 1-cm-thick interstellar tray. The trays are filled with newly invented continuous gradient and layered gradient density silicate aerogel capture cells. To monitor the space environment three compounds (an aluminum and a sapphire disk and an interstellar aerogel) are mounted on the STA deployment arm away from Wild 2 particles as shown in Figure 8.

6. Science Investigations

[54] Stardust's science investigations are focused to collect samples from the comet Wild 2 and return them to Earth for detailed laboratory analyses. All other investigations and shared engineering capabilities provide important context for the captured samples. ISP collection is bonus science given it uses the same Wild 2 sample instrument and operates during quiescent cruise periods. The five Stardust dedicated and shared science payloads are the following: (1) Wild 2 and Interstellar Sample Collection and Earth Return [*Tsou et al.*, 2003]; (2) Comet and Interstellar Dust Analyzer [*Kissel et al.*, 2003]; (3) Dust Flux Monitor including a Dust Shield Dust Flux Monitoring [*Tuzzolino et al.*, 2003]; (4) NavCam shared engineering Optical Navigation Camera [*Newburn et al.*, 2003a]; and (5) Dynamic science shared engineering communication and attitude control subsystems [*Anderson et al.*, 2003]. Detailed description of each payload is found in respective papers in this special section.

6.1. Wild 2 and Interstellar Sample Collection and Earth Return Instrument

[55] The ability to capture hypervelocity particles intact as extensively demonstrated [*Tsou*, 1990]. Silica aerogel has

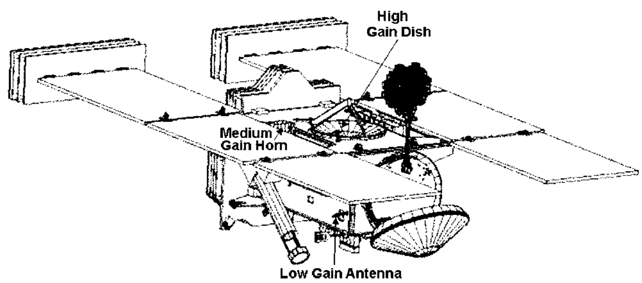

Figure 7. Stardust communication antennae: 3° high-gain dish, 7 medium horn, and 45° low gains.

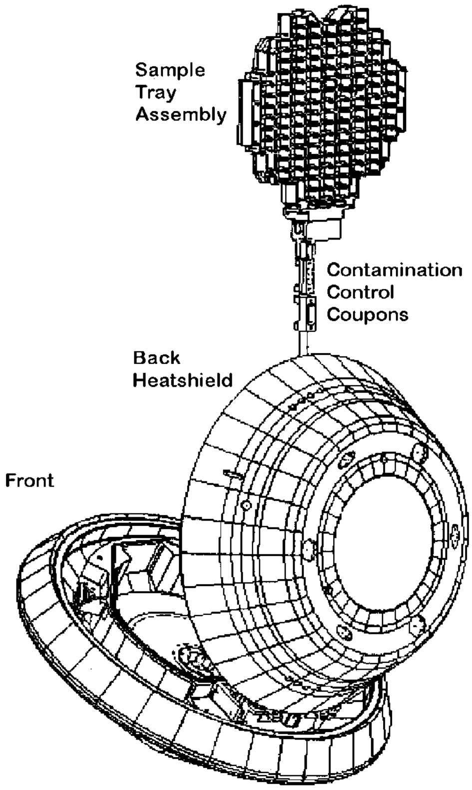

Figure 8. Stardust sample subsystem showing the interstellar of the sample tray assembly, wrist motor, contamination control coupons, shoulder motor, one of two main heat shield latches, and the main heat shield.

been shown to be effective for intact capture of particles at 6 km/s in the laboratory and in Earth orbital experiments [*Tsou et al.*, 1993; *Brownlee et al.*, 1994b]. For Stardust, a technique to produce continuous gradient density aerogel had to be invented to meet the engineering volumetric limitations. To maintain aerogel cell integrity, ease of sample distribution, and handling of captured particles, the aerogel collection area is divided up into 130 2 $\times$ 4 cm rectangular and 2 trapezoidal cells. The targeted variable aerogel density for the Wild 2 side is 5 mg/ml to 50 mg/ml and 2 mg/ml to 20 mg/ml for the interstellar capture cells and the largest targeted particles 100 μm and 10 μm in diameter, respectively. Pure aluminum foils 100 μm thick are wrapped around the walls of the sample trays frames to facilitate cell removal and are also excellent small particle collectors. The Wild 2 and interstellar trays are mounted back to back, with total exposed aerogel surface area of 1039 cm^2 and 1037 cm^2, respectively. The total exposed aluminum foil is about 15% of the exposed aerogel surface area. The front tray assembly of 3 cm thick will be exposed to the Wild 2 samples while the back tray of 1 cm thick will capture the samples from the ISP stream.

6.2. Comet and Interstellar Dust Analyzer

[56] The CIDA instrument, provided by Germany's DARA, is mounted outside of the spacecraft bus, as shown in Figure 5. CIDA utilizes the technique of impact ionization mass spectrometry to analyze thousands of particles and has several important improvements over its predecessors: the maximum target area is increased from 5 cm^2 to 100 cm^2, to accommodate the low flux of interstellar grains, and the spectrometer can be periodically switched to analyze positively charged ions from the standard setting for negative ions. Owing to the much lower flyby speed at Wild 2 than for Halley (6.1 km/s versus 70 km/s), the impact ion spectra from a given particle are expected to be far more complex with more contributions from molecular ion species [*Kissel et al.*, 2003]. Enhanced sensitivity to molecular species is of major potential value, especially if CIDA detects relatively volatile molecular species, which would not be expected to be retained in the aerogel cells.

6.3. Dust Flux Monitor

[57] The dust flux investigation utilizes a stand-alone flux monitoring instrument that is a duplicate of the High Rate Detector of the Cosmic Dust Analyzer instrument on the Cassini mission. This unit utilizes 200 cm^2 of 25 μm and 20 cm^2 of 6 μm polyvinylidene fluoride, electrically polarized film, to detect impacts and classify them into seven distinct particle mass thresholds ranging from 10^{-11} to 10^{-3} g [*Tuzzolino et al.*, 2003]. In addition, half of the spacecraft main Whipple shield within the launch adapter ring is instrumented with two quartz piezoelectric acoustic sensors (PCB Piezotronics No. J351B31) to detect very large particles with calibrations performed at Canterbury University at Kent [*McDonnell et al.*, 1999]. The frontal view of the Stardust spacecraft in Figure 9 shows the location of the Dust Flux Monitor sensors. The front acoustic sensor is mounted on the center line of the bottom half of the front bumper dust shield within the launch adapter ring and the second sensor on the circular acoustic plate attached to the first Nextel curtain behind the front bumper shield.

6.4. Imaging Camera

[58] In order to accurately guide the Stardust spacecraft to the nucleus of comet Wild 2 beyond radio navigation (2500 km in the B-plan), optical navigation by NavCam is needed. After having reached the comet nucleus, NavCam's engineering function is completed and the camera will acquire a series of high-resolution images (59.4 mrad/pixel) of the Wild 2 nucleus during the 150 km flyby. The navigation camera is the fourth Voyager Wide Field Camera body with replaced 1024 $\times$ 1024 CCD array having an instantaneous field of view of 0.08 milliradian per pixel. The camera will be used to acquire images of the nucleus with a resolution an order of magnitude better than the Giotto images of P/Halley. The camera is fixed to the spacecraft but a scan mirror provides one axis rotation to track the nucleus during the flyby as shown in Figure 6. Owing to the high flyby speed, a nucleus tracking algorithm has been developed for DS 1 to track comet Borrelly and tested successfully during the Stardust Annefrank flyby. A flyby of Wild 2 at 150 km will allow resolution <20 m.

6.5. Dynamic Science

[59] The dynamic science investigation uses shared engineering hardware for scientific observations, namely the telecommunication X band transponder and the attitude control subsystems. The X band transponder was manufac-

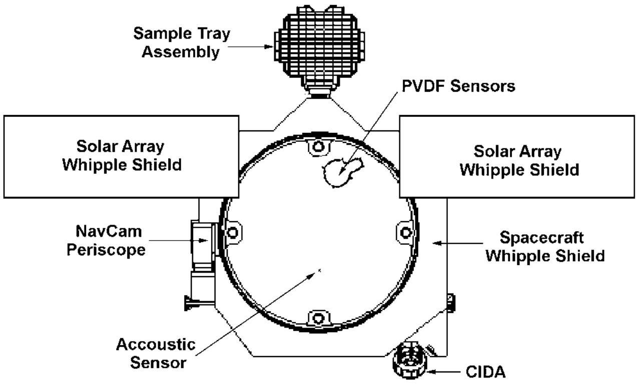

Figure 9. Frontal view of the Stardust spacecraft showing the dust flux monitor polyvinylidene fluoride and acoustic sensor locations.

tured by Motorola and developed for the Cassini project. The upper limits of Wild 2 mass will be estimated with the frequency shifts in coherent two-way X band communication signal. The integrated dust flux and large particle impacts will be derived from Honeywell Initial Measurement Unit (gyro and accelerometer for each of the three axes) that enable the spacecraft attitude control subsystem maintaining the ±2° attitude band.

7. Science Return

[60] The Stardust science is focused in the collection of Wild 2 coma samples and their return to Earth for detailed laboratory analysis. The in situ encounter investigations provide the broad context to the primary sample science. The remaining cruise science is target of opportunities. The Stardust science requirement document established the science investigations for the entire mission [*Tsou*, 1995].

[61] Sample analyses require experienced analysts, complex instrumentations, and time consuming and intricate processes. No single laboratory or scientist can provide the full range of analytical capabilities required to study these returned samples. Experience has shown that organized consortia performing carefully planned sequential studies on samples are exceedingly productive for analyzing complex and rare extraterrestrial materials. Often a high degree of synergy develops among disciplines, providing techniques and results not previously imagined possible. Dispersal of the samples to a broad community also spurs competition, which leads to new innovations as well as to careful checking and validation of results. Consequently, the full Stardust science return from the returned samples will come years after extensive study by the world's sample community. As part of the Stardust proposal, the returned Wild 2 samples will be documented and given a preliminary examination after recovery. Results of the preliminary examination of the Wild 2 samples will be reported within 9 months of the recovery. At that time, at least 75% of the Wild 2 samples will be turned over to the NASA Office of Curator for safekeeping and distribution to the scientific community. Results of the preliminary examination of the interstellar samples will be reported 1 year later, in September 2007 along with the transfer of at least 75% of the interstellar samples.

[62] All of the in situ science investigations will deliver the flight data and calibrations necessary for data reduction to the NASA Planetary Data System (PDS) within 6 months of their acquisition. After the validating the delivery, PDS will make these data available to the scientific community.

7.1. Cruise Science

[63] The cruise science during the majority of the 7-year mission consists of the interstellar sample collections most significantly, CIDA measurements of particles from the ISP stream. An important additional value of having both CIDA and sample of ISP is that analyses of returned particles can be used for "ground truth" comparisons with in-flight CIDA results, something not possible previously.

[64] The design of the Stardust trajectory incorporated the possibility for a flyby to the asteroid Annefrank near the end of the second orbit about the Sun [*Tsou et al.*, 1994]. This possibility offered an excellent opportunity for an in flight rehearsal for the Wild 2 encounter and gaining some knowledge of this little known asteroid with very little delta v cost. Since the amount of ground testing was limited before launch, this flyby rehearsal was the first time that the entire Wild 2 hardware and encounter software would be exercised at the same time. Having an in-flight rehearsal enhanced the probability of a successful Wild 2 encounter. This successful flyby took place on 2 November 2002 at a distance of 3078 km. In addition, to a beneficial exercise of the Wild 2 encounter sequence, a series of images were acquired that allows Annefrank's size, shape, albedo and as well as the phase function out to 134° were determined [*Newburn et al.*, 2003b].

[65] There are also five opportunities of solar conjunctions, four oppositions, and one Earth gravity anomaly investigation for dynamic science. A summary of these dynamic science investigations is shown in Figure 10, a heliocentric Stardust trajectory plot in a rotating coordinate frame.

7.2. Encounter In Situ Science

[66] CIDA will record the elemental and isotopic composition of Wild 2 particles impacting its target concomitant to WISCER sample collection. CIDA is more sensitive and has a larger collecting area than the similar instruments on the Halley probes, but the impact speed is much lower. The composition of the rocky material, the relative abundance of carbon and the nature of the organic refractory material for Wild 2, can be compared with the dust composition from Halley, an Oort cloud comet. Moreover, the in situ compositional measurements and the compositional analyses of the returned samples complement each other and provide a valuable crosscheck. This could lead to improved understanding of PIA and PUMA measurements at comet Halley. For example, CIDA may detect certain volatile organics that would not be retained in the aerogel. This can be the first complete composition profile of a comet flythrough, important in its own but also very useful in deconvolving the time compressed samples collected by WISCER.

[67] The Dust Flux Monitor will measure the mass distribution of dust in the coma and the spatial distribution along the trajectory. These data can be compared with similar measurements of comet Halley, a much larger and more active comet. The measured Wild 2 dust fluence will

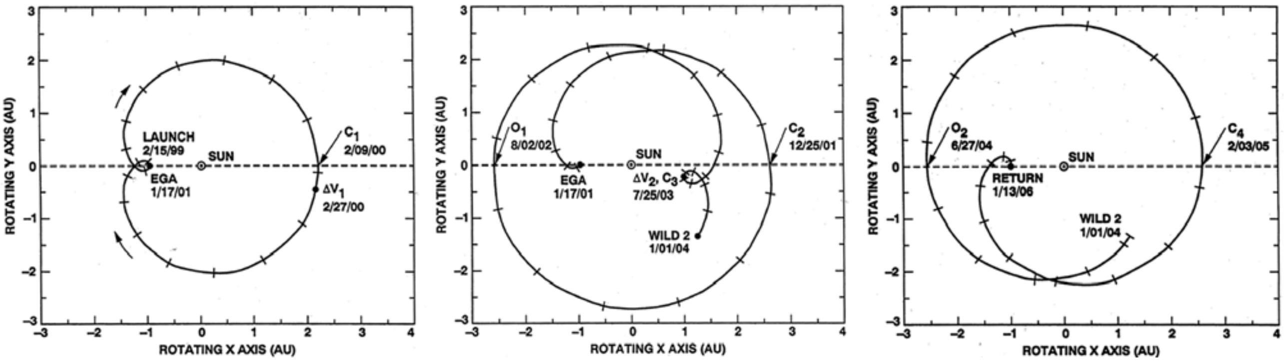

Figure 10. Stardust dynamic science events, showing four solar conjunctions (C), two solar oppositions (O), and one Earth Gravity Assist.

allow an estimate of the number of captured particles and the mass distribution will be a valuable guide for resolving captured particles at different times. The spatial distribution can be compared with coma morphology in the approach images to identify jets and locate active areas on the nucleus. Large particles are of the most interest, because they may carry much of the mass lost by the nucleus. Piezoelectric sensors mounted on the spacecraft's main dust shield will be sensitive to impacts over a larger collection area (0.38 m^2) and will record impacts by larger particles. This time series information will provide valued ground truths to cometary dust flux models and understanding of the cometary sublimation process but also important key to resolve the time-compressed samples on WISCER helping to separate early, middle, and departing samples by size.

[68] The flyby of comet Wild 2 at the close range of 150 km will allow the NavCam to obtain images over a 178° range of phase angles with a resolution down to about 20 meters/pixel, and would be the highest resolution yet achieved for a cometary nucleus [*Newburn et al.*, 2003a]. From the Wild 2 images, the size, shape, albedo, and surface morphology of the nucleus can be determined. The phase function over the full 178° range in phase angle

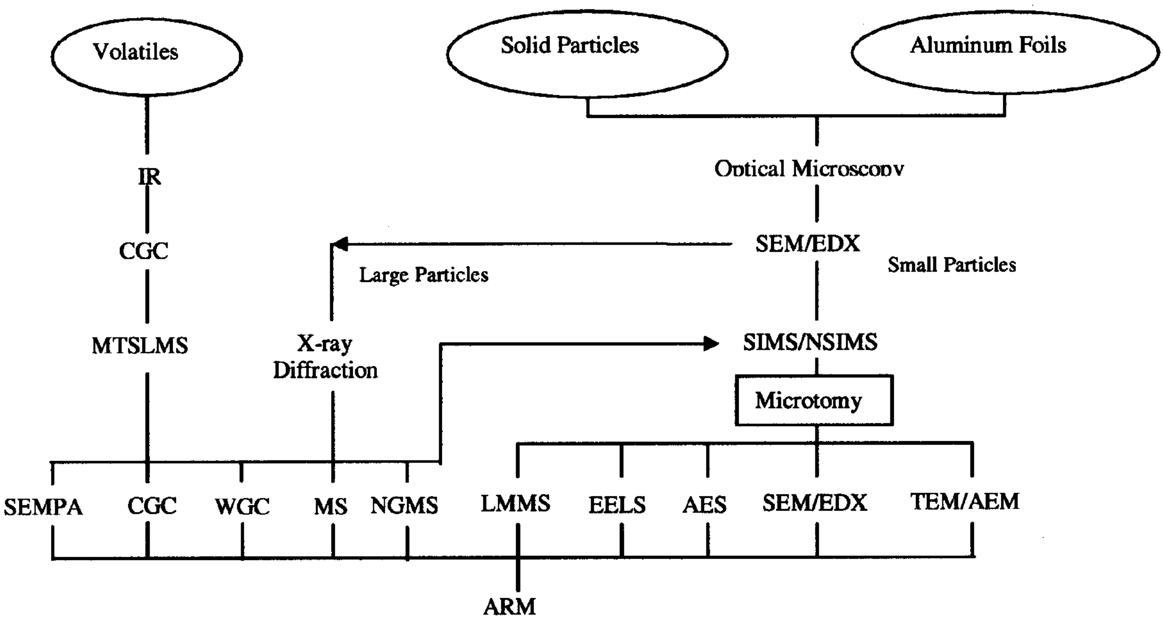

Figure 11. Baseline particle examination procedure. IR, IR spectrometry; CGC, CIDEX gas chromatography; MTSLMS, microprobe two-step laser mass spectroscopy; SEM, scanning electron microscopy; EDX, energy dispersive X ray; TEM, transmission electron microscopy; NSIMS, nano secondary ion mass spectroscopy; SEMPA, scanning electron microprobe microscopy; WGC, wet chemical gas chromatography; MS, mass spectroscopy; NGMS, noble gas mass spectroscopy; LMMS, laser microprobe mass spectroscopy; EELS, electron energy loss spectroscopy; AES, auger electron spectroscopy; AEM, analytical electron microscopy; ARM, atomic resolution microscopy.

Table 1. Questions for Wild 2 Sample Analysis

Specific Subject	Questions Answered
Amino acids	Exist? Other biogenic molecules?
Carbon	What is the form? Isotopic composition? Location? Any organic refractory mantles on grains? What compounds dominate? Similar to ones found in IDPs?
Mineral content	Mineralogy of Wild 2? What is the amorphous/crystalline silicate ratio?
Presolar grains	Are there grains with large nonsolar isotopic effects?
CAIs and chondrules	Any found? Some fragments found? Pyroxene-rich aggregate found?
Compositions	What are the elemental, chemical, isotopic, and mineralogical compositions at the nanometer and larger scales?
Cosmic ray tracks	How abundant? Any other evidence of radiation?
D/H	What is the average and specific D/H? Are there hot spots similar to those seen in IDPs?
Diamonds	Are there nanodiamonds? Are they comparable to those seen in meteorites?
Forsterite and enstatite	How abundant? Comparable to carbonaceous chondrites and IDPs?
Fractionation trends	Comparable to meteorites? In Ca, Al, and Ti refractories? In Fe/Si?
GEMS	Exist? How abundant?
H_2O	What state? Hydrated minerals?
He	What is the concentration? Are there $^3He/^4He$ indicative of long-term spallation, implanted solar wind or presolar stellar winds?
Hydrated minerals	Do they exist? Were they formed by gas-grain reactions or by aqueous alteration?
IDPs and meteorites	Similarity to Wild 2? Fraction of preserved IS grains?
Nebula mixing	Evidence of inner high-temperature condensates?
$^{14}N/^{15}N$	Are these effects common? Large effects found in IDPs?
Nitrogen	In molecular form? Isotopic ration? Location?
Nobel gases	What are Xe, Kr, and Ar abundances? What isotopic composition?
Organics	Processing signatures? Condition of processing? Relationships to other mineral phases?
Oxygen isotopes	What is the composition and range? Large effects in IDPs?
Aerogel capture efficiency	Effectiveness for solid grains? In fluffy grains? Preservation of PAHs? Surface retentions?
Foil capture efficiency	Effectiveness in capturing small particles? Survival rate for solid grains and for nonsolid grains? Any morphology modifications?

will allow inferences about the physical properties of the surface. These results can be compared with results from the DS-1 flyby of comet Borrelly; the integrated geometric albedo of Borrelly was only 0.03, but the albedo varied by up to a factor of 3 over the surface (B. J. Buratti et al., Deep space 1 photometry of the nucleus of comet 19 P/Borrelly, submitted to *Icarus*, 2003). With the images of the active regions, a better understanding of the sublimation process and clues to interpret the captured samples and assess the degree of samples representation of the Wild 2 nucleus. Dust particles provide a sample of compositions of the nucleus; images provide the view of the entire nucleus, which will be essential context for sample interpretation. The images will also provide the critical data to associate the collected samples with a particular type of comet if different types can be identified by future comet studies. There is every reason to believe that comets are diverse objects [*Whipple*, 1991], somewhat analogous to the different classes of asteroids. With these data one can determine the size and shape of, the fraction of the surface that is

Table 2. Questions for Interstellar Sample Analysis

Specific Subject	Questions Answered
Carbon	What is the form? Isotopic composition? Location?
CAIs and chondrules	Any found? Some fragments found?
Compositions	What are the elemental, chemical, and mineralogical compositions?
Cosmic ray tracks	How abundant? Any other evidence of radiation?
D/H	What is the average and specific D/H? IDP can be as high as 6×104/mil?
Diamonds	Are there nanodiamonds? Comparable to meteorites?
Forsterite and enstatite	How abundant? Comparable to IDPs?
Fractionation trends	Comparable to meteorites? In Ca, Al, Ti refractories? In Fe/Si?
GEMS	Exist? Similar glassy or crystalline? How abundant?
Graphite	Prevalent? Abundant enough to explain 0.22 μ extinction bump?
He	What is the concentration? 10 cc/g is high in IDPs. What is the intrinsic 3He/4He? Solar is 4×10^{-4}.
Hydrated minerals	Any found?
IDPs and meteorites	Fraction of preserved IS grains?
Isotopic composition	Composition for H, C, N, O, Mg, and Si? Anomalous?
$^{14}N/^{15}N$	Are these effects common? Large effects found in IDPs?
Mineralogy	Physical mixing of phases?
Nitrogen	In molecular form? Isotopic ration? Location?
Nobel gases	What is Xe, Kr, and Ar abundance? What isotopic composition?
Oxygen isotopes	What is the composition and range? Large effects in IDPs?
Processing signatures	Shock, collision, accretion, chemical alterations? Thermal or aqueous processing?
Aerogel capture efficiency	Effectiveness for higher speed solid grains? Organics survived? Vaporization?
Foil capture efficiency	Effectiveness in capturing higher speed grains? Survival rate?

active, the structure and texture of the nucleus surface, and variations of albedo and color across the surface. It will also obtain information on surface characteristics over a range of phase angles (70° to 2° then to 110°) [*Newburn et al.*, 2003a].

[69] CIDA has 100 cm^2 sensor surface, Dust Flux Monitor 220 cm^2 sensor surface, and WISCER 1039 cm^2 of aerogel surface; the spacecraft dust shields have a total 2.05 m^2 of cross sectional sensing area for dust impacts. Viewing a wider "window" of cometary dust, the X band transponder signal will provide Doppler shifts to ascertain an integrated dust flux. During the closest Wild 2 encounter, the gyroscope and the accelerometer of the attitude control subsystem will provide sensing for larger impacts [*Edenhofer et al.*, 1987]. In effect, the entire three dust shields become dust impact sensors, albeit for only larger particles.

[70] The entire suite of Stardust in situ science investigations will be compared with the first full fledged comet flyby missions to Halley (Giotto and Vega I & II). Valuable cross comparisons will clarify our understanding of comets and discover discrepancies and new findings. Stardust will have the Wild 2 samples, providing unique ground truth for Stardust in situ instruments.

7.3. Samples Science Return

[71] The objective of Stardust sample collection is to collect both Wild 2 and interstellar particles with the least degradation of the grains possible while remaining within a restricted capture medium thickness. A Preliminary Examination Plan (PEP) (P. Tsou, unpublished data, 2002), describes in details the processes, schedule, and budget for the documentation and preliminary examination of the returned samples from the Stardust WISCER. The operation of this plan extends from the landing of the SRC on 15 January 2006 to the delivery of the Stardust preliminary findings. Samples of Wild 2 and contemporary ISP and in situ data from Stardust will provide the opportunity for significant scientific understanding in areas of key interest to planetary science, astrobiology, and astrophysics.

[72] The Preliminary Examination Team (PET) consists of Stardust sample Co-Is, science advisors, and invited guest analysts, led by the WISCER Lead. The PET has the following objectives: (1) develop procedures and perform complete recovery and postflight documentation of the WISCER and returned samples; (2) develop procedures and perform preliminary examination of the allocated samples; (3) provide the LMA contractual statistical determination of the total number of intact cometary particles greater than 15 microns in diameter; (4) determine the recovered states of the collected samples and the levels of alteration by the capture process; (5) document the collection environment and the levels of contamination; (6) perform an assessment of the aerogel and aluminum foil capture performance; and (7) prepare a report to NASA documenting the preliminary findings from the returned cometary samples in September 2006 and from the interstellar samples in September 2007.

[73] The Stardust PET will perform the preliminary examination (PE) under two constraints: (1) a period of performance (9 months for Wild 2 samples and an additional year for the interstellar samples) and (2) the number of aerogel samples to be analyzed (≤25% of the total returned samples). The PE is limited in scope, but a comprehensive report of the Stardust sample finding will be made. For most of the samples, baseline analysis flow will be followed as shown in Figure 11.

7.3.1. Wild 2 Sample Results

[74] Through analysis of the Stardust Wild 2 samples, researchers will be able to address the questions shown in Table 1 concerning comets.

7.3.2. Interstellar Sample Results

[75] Capture of analyzable ISP is expected for encounter speeds below about 10 km/s, a condition that is met during only about 30% of the interstellar collection time. The more refractory components of the grains should survive sufficiently to give compositional and mineralogical information. It should be possible to determine the elemental and the isotopic composition of H, C, O, Mg and Si; the prevalence of graphite grains; the presence of SiC grains; and the extent of physical mixing among mineral phases. CIDA may also provide in situ data on the elemental and isotopic composition of individual particles. Through analysis of the ISP samples, answers will be derived from the questions shown in Table 2.

7.3.3. Sample Distribution and Curation

[76] Since Stardust will return the world's first samples of cometary and contemporary ISP, sample allocation and decisions about sample distribution after the PET reports will be made by the NASA Stardust Oversight Group in coordination with CAPTEM. Stardust highly recommends that a portion of the returned samples be put away for a delayed distribution, i.e., approximately a decade, to allow the incorporation of new techniques, new analysts, and new perspectives. When evaluating sample requests for approval, the Stardust Oversight Group should also consider such criteria as access to analytical facilities, analytical experience, the scientific value of the proposed analyses, and sample quantity requirements that maximize science return per sample, while preserving an adequate quantity of samples for future studies.

8. Conclusion

[77] In summary, Stardust will return samples that will present critical links between several areas of study of comets, ISP, and solar system formation. The returned samples should furnish important insight into the nature and amount of dust released by comets and the links between a known cometary body, Wild 2, and meteoritic samples, i.e., meteorites and IDP collected at Earth. The measured properties of cometary dust should provide important clues to the importance of comets in producing dust in our zodiacal cloud as well as circumstellar dust around other stars. Together Stardust with other cometary missions will contribute fundamental insights into the comets and their past and present roles in planetary systems.

[78] **Acknowledgments.** Stardust is the culmination of a quest for samples from a comet coma since 1982. Many scientists, managers, engineers, technicians, and benefactors who were either touched by this quest or shared the dream have assisted and lent critical hands at critical moments. As a project, Stardust required skilled cooperation from its partners; they are the Principal Investigator from the University of Washington, spacecraft, sample capsule, and operations teams from LMA, and

mission design, navigation, and management teams from JPL. The launch team from KSC performed faultlessly. On return, full support will be required from UTTR and the post flight processing support from the Office of Curation at JSC. Editing help from J. R. Weiss is appreciated. This research was carried out under a contract with the National Aeronautics and Space Administration.

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