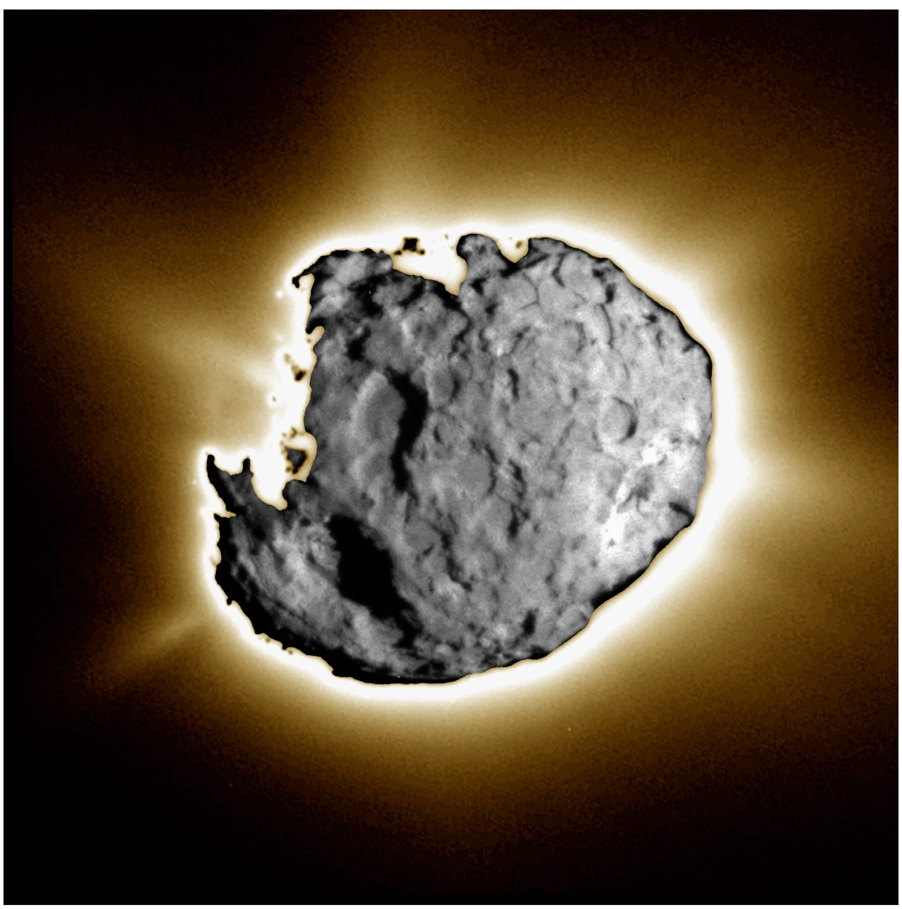
The *Comet Coma Rendezvous Sample Return* (CCRSR) Mission Concept – The Next Step Beyond *Stardust*

Scott A. Sandford,[1] Michael A'Hearn,[2] Louis J. Allamandola,[1] Daniel Britt,[3] Benton Clark,[4] Jason P. Dworkin,[5] George Flynn,[6] Danny Glavin,[5] Robert Hanel,[1] Martha Hanner,[7] Fred Hörz,[8] Lindsay Keller,[8] Scott Messenger,[8] Nicholas Smith,[9] Frank Stadermann,[10] Darren Wade,[9] Ernst Zinner,[10] and Michael E. Zolensky[8]

[1] NASA-Ames Research Center
[2] University of Maryland
[3] University of Central Florida
[4] Space Sciences Institute
[5] NASA-Goddard Space Flight Center
[6] SUNY at Plattsburgh
[7] University of Massachusetts
[8] NASA-Johnson Space Center
[9] Lockheed Martin, Denver
[10] Washington University @ St. Louis

Principal Author: Scott Sandford
NASA – Ames Research Center
Phone: 650-604-6849
Email: Scott.A.Sandford@nasa.gov



Abstract

The Stardust Comet Sample Return Mission successfully returned particles from the coma of Comet 81P/Wild 2, providing a host of important new insights into the nature of cometary materials and the processes which formed our Solar System. These samples have important limitations, however, because they were collected in modest numbers at harsh hypervelocities and represent a one-time random sampling of the coma (a "grab" sample). Here we describe a next generation mission, the Comet Coma Rendezvous Sample Return (CCRSR) mission designed to take the next major scientific leap in the acquisition and study of comet samples. This mission utilizes a spacecraft designed to rendezvous with a comet, make extended observations within the cometary coma (but not land on the comet), gently collect multiple coma samples representing different source sites, and return them to Earth for study. Samples returned by CCRSR would have major scientific advantages over those returned by Stardust. First, the samples will be captured at far lower velocities, eliminating sample destruction and alteration during collection, and resulting in the return of much more pristine material, especially organics and fragile minerals. Second, CCRSR will collect *separate* samples of dust from the general coma and specific individual jets spanning months of cometary activity and will provide a more representative sampling of the entire comet as well as isolated samples corresponding to activity specific in time and space. Finally, CCRSR will collect orders of magnitude more sample, thereby vastly improving statistics and increasing chances of collecting rare materials of high diagnostic value. This mission would greatly expand our knowledge of cometary activity and provide robust quantities of the Solar System's most pristine materials for extensive study.

A. The CCRSR Mission Science Objectives

It is now understood that our Solar System formed from the collapse of a portion of a dense interstellar molecular cloud of gas, ice, and dust [1]. The collapsing material formed a disk surrounding a central protostar, and from this disk the planets, comets, and asteroids formed [2, 3]. The importance of these small bodies far outweighs their minor contribution to the mass of our Solar System. All the material that ended up in the planets has been thoroughly reprocessed since these bodies formed, and they can provide only limited insights into the nature of the starting materials from which they were made. Smaller bodies like asteroids and comets have undergone considerably less parent body processing and contain more pristine samples.

Comets are thought to have accreted in the colder, outer, less processed regions of the nebula. Comets, therefore, probably contain a more representative portion of the components of the original protoplanetary disk, particularly volatiles, and likely have undergone less parent body processing since formation [3]. Thus, cometary materials likely represent the best samples of pristine early Solar System materials available for study and may provide powerful insights into the formation of the entire Solar System, not just comets. Cometary materials are also of great astrobiological interest, since these bodies may have delivered key volatiles and organics to the early Earth that may have played a role in the origin and evolution of life [4]. Finally, since the composition of comets is the end result of a series of universal processes involving stellar, interstellar, and star-forming environments, their compositions should be generally representative of the compositions of these bodies in other stellar and planetary systems. Thus, insofar as comets inform us about the origin of our Solar System and life on Earth, they would be expected to play a similar role for other planetary systems. Understanding comets in this context may, therefore, provide insights into more universal processes and environments.

Our current understanding of comets and their components is the combined result of information gathered using telescopic remote sensing (largely spectroscopic) techniques, laboratory simulations, spacecraft flybys of individual comets, the study of meteoritic materials found on Earth (Fig. 1), and the study of samples returned to the Earth from Comet 81P/Wild 2 by the Stardust spacecraft. The samples returned from Comet Wild 2 have greatly expanded our understanding of comets and have confirmed at least some of our expectations. These samples show that Comet Wild 2 was made of a highly heterogeneous mixture of both minerals and organics that are far from being in chemical and mineralogical equilibrium. Both highly volatile and highly refractory components were present in the collected cometary particles, often in mixtures in which these components were in intimate contact and intermingled on micron size scales [5-10]. Some of these phases also showed clear isotopic evidence for presolar materials. The results of these studies have amply demonstrated that: (i) comets contain materials that formed in a wide variety of environments that likely spanned the entire solar nebula, as well as presolar interstellar and circumstellar environments; and (ii) these materials were subjected to very little processing after they were accumulated into the cometary parent body, a strong confirmation of the idea that comets represent repositories of 'primordial' solar system materials.

While the Stardust aerogel collectors did an impressive job of collecting particles from the coma of Wild 2 (Fig. 2), the Stardust samples suffer from several important limitations. Wild 2 particles, thought to be similar to the one shown in Figure 1, struck Stardust aerogel at ~6.12 km/s. At this velocity, some of the impacting material was destroyed, some was altered, and some survived unaltered [5, 6, 9, 10]. This greatly complicates the interpretation of data obtained from the returned samples; it is not always clear whether sample compositions and structures are characteristic of material original to the comet, have been altered from their original forms, or contain processed aerogel collector material. This makes it difficult to ascertain the relative abundances of different cometary materials since there has likely been selective loss/alteration of some components over others (for example, impact probably selected against the pristine survival of many organics [9]). Thus, while we will continue to learn more about comets from the Stardust samples, these samples will never allow us to address a number of key questions about cometary and early Solar System materials. These include questions like – (i) What is the relative proportion of minerals and organics?, (ii) Are volatile organics present?, (iii) What radiometric chronologies can be established for comets?, and (iv) Are nebular condensate amorphous silicates present? (a question difficult to address with Stardust samples collected in aerogel, which is itself an amorphous silicate).

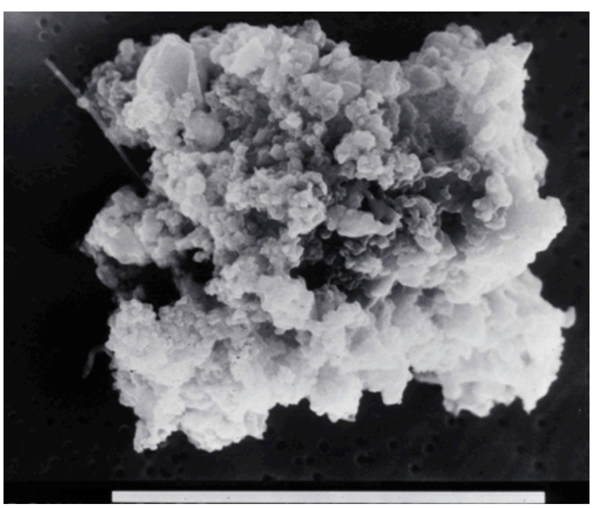


Figure 1. An interplanetary dust particle thought to come from a comet (10 μm scale bar). CCRSR would return vast numbers of more pristine particles from selected cometary source regions for study in terrestrial laboratories.

CCRSR builds on the successes of Deep Impact and Stardust. It will greatly expand on the Stardust sample return in three main ways. First, it will return much more material than Stardust did. Stardust returned less than 1000 large particles (>15 um), and <0.05 milligram of total material [5]. CCRSR will be able to collect and return over 100 times as much material because of its much closer approach distances and far longer collection times. Collection will occur on high purity metallic meshes, avoiding the organic contaminants, extraneous particles, and ubiquitous Si and O of Stardust aerogel. These factors will eliminate many of the analytical challenges of Stardust samples and greatly advance the scientific results. Most importantly, the greater sample sizes will have the benefit of (i) vastly improving statistics associated with particle types, (ii) providing a far more representative sampling of the entire comet, (iii) providing the ability to carry out analyses that require larger samples (for example, adequate isotopic chronologies and the identification of specific organic species, and (iv) increasing chances of collecting rare materials that may be of high diagnostic value (the detection of a single small grain of osbornite, a vanadium nitride mineral, in a Stardust sample played a major role in demonstrating that large scale mixing was a major process in the early solar nebula).

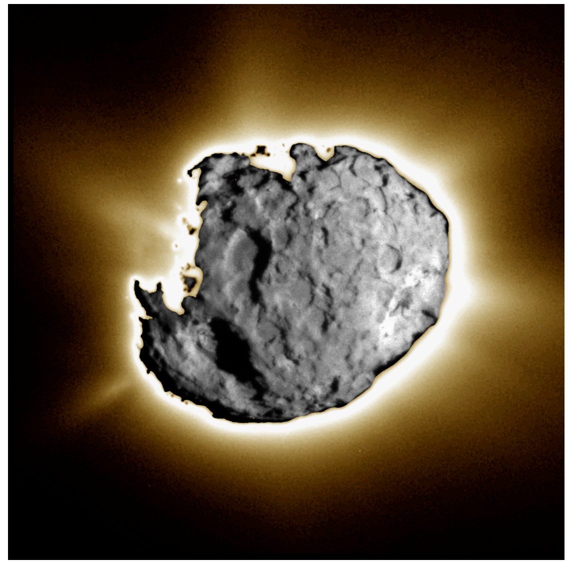


Figure 2. A composite image of Comet 81P/Wild 2 that shows the surface of the cometary nucleus and many of the comet's dust jets. CCRSR will capture dust from jets and inter-jet regions from a comet at different orbital epochs. CCRSR will also obtain images with high spatial resolution at intervals in the comet's orbit to establish the temporal activity and sources of jets.

Second, the CCRSR samples will be collected at impact energies that are more than a factor of a thousand less than those for samples collected by Stardust (CCRSR collection velocities will be <0.1 km/s for large grains versus 6.1 km/s for Stardust). Thus, CCRSR samples will suffer little to no alteration during collection, thereby providing a more pristine and unbiased sample of cometary material. This will assist greatly with the study of volatile species and organics.

Finally, the CCRSR samples will be obtained over a larger time frame. All the Stardust samples were collected in an ~10-minute interval and sampled material from only a few cometary jets. CCRSR will collect samples over an extended period (pre-perihelion to post-perihelion) and will provide a much more representative sample of the comet as a whole. In addition, since CCRSR will expose different collectors at different times, we will be able to study if the material in the coma varies with time, cometary activity, source region, etc., and test whether the material in separate jets differs from each other or from diffuse coma material.

In addition to the primary science goal of returning cometary samples to Earth, the mission also has a number of secondary scientific goals associated with placing the returned samples in their proper cometary context. These goals are addressed by a number of instruments that will make *in situ* measurements while in the vicinity of the comet. These instruments, which are discussed in more detail later, include a dust flux monitor, a neutral and ion mass spectrometer, and a set of wide and narrow angle cameras. These instruments will be used to characterize the nucleus of the comet, monitor its activity with time, assist with the sampling flybys, and put the returned samples in context with their sources (specific jets, for example).

Thus, our scientific approach is to mandate a sharp focus on the top mission science priority of definitively collecting separate populations of emitted cometary material for analysis on Earth. Instruments will also observe cometary activity at a stand-off distance and periodically emerging from such periods of low level monitoring activity to more closely image jet activity, measure dust and gas emissions, and make collection sorties to targeted coma locations, including jets.

Relevance of the CCRSR Mission Science to NASA – Comet Surface Sample Return (CSSR) was called out as one of the highest priorities for missions to Solar System bodies in the last Decadal report. In addition, comet sample return is listed as being a "major or unique contribution" to three of the five major science questions called out in the Traceability Matrix in Table 3.1 of the NASA Roadmap. Although the spacecraft would not directly contact the surface, the CCRSR Concept Mission would return cometary surface and subsurface materials ejected from a known comet and will be able to relate these directly to cometary activity. As such, this mission concept is highly relevant to addressing multiple NASA goals.

B. CCRSR Mission Implementation

B.1. Science Targets and Overall Mission Approach

The Comet Coma Rendezvous Sample Return (CCRSR) mission could potentially target any comet with which it can rendezvous. For orbital and length of mission considerations, this largely restricts the potential targets to comets in prograde orbits near the ecliptic plane like Jupiter class comets. The target comet therefore depends on the available launch window; for the CCRSR DSMCE concept study, the optimal target was Comet 46P/Wirtanen. In the overall mission design, the spacecraft launches from Earth, matches orbits with the comet, follows it for a significant part of an orbital period, and then returns to Earth. While in the vicinity of the comet the spacecraft spends most of its time monitoring the nucleus and its associated activity from a safe standoff distance. At appropriate times, the spacecraft 'dips' down into the cometary coma to make closer visual observations, measure dust and gas emissions, and carry out its primary task of collecting samples from targeted coma locations, including the outflows of jets.

B.2. The CCRSR Discovery/Scout Mission Capability Expansion Concept Study

The Comet Coma Rendezvous Sample Return (CCRSR) mission was one of the mission concepts funded for study under the Discovery/Scout Mission Capability Expansion (DSMCE) Program. As a result, this mission benefits significantly from having been matured through a concept study that explored all aspects of the mission's science goals and implementation. A full Concept Study Report for this effort was delivered to NASA Headquarters in Feb 2009. The scientific aspects of the mission were addressed by the study PI (S. Sandford) and CoIs (M. A'Hearn, L. Allamandola, D. Britt, B. Clark, D. Cruikshank, and M. Zolensky), a team with extensive experience that includes expertise on comets, comet missions, and comet sample return. This team also includes members with extensive experience in the study and curation of extraterrestrial samples, including cometary samples. The study of the technical aspects of the mission were carried out by Lockheed Martin. This study was designed, in part, to study whether the use of an Advanced Stirling Radioisotope Generator (ASRG) for spacecraft power was feasible and justified. Much of the discussion of mission implementation that follows represents results from the DSMCE study. This study established that CCRSR requires no major technology development and that it could use science instruments and spacecraft components having significant heritage. Studies are also ongoing to determine how a non-ASRG, solar panel powered version of this mission might be implemented. These studies indicate that the CCRSR fits within the Discovery or New Frontiers mission classes.

B.3. Science Instruments Payload

Although only a minimal payload is required for this mission, its value will be unusually high because of two factors. First, most of the dust science will be accomplished back on Earth with cross-disciplinary, state-of-the-art analytical instruments. Second, the long-lived mission in the vicinity of an active comet vastly multiplies the value of the spacecraft's instruments because they will systematicly monitor and thoroughly document a full cycle of cometary activity.

The primary instrument carried by the CCRSR spacecraft is the dust sample collector. Secondary instruments for *in situ* measurements include narrow- and wide-angle cameras, a dust flux monitor, and a mass spectrometer. The cameras and the dust flux monitor carry out dual roles, both as the collectors of direct science data and as devices to help plan and verify success of the primary science task of collecting the cometary samples.

While responsible for attaining the primary science objective for the mission, the dust collector is a payload of only modest complexity since it need only collect the particles, not analyze them. Actual sample analysis will be accomplished back on Earth in laboratories around the world. Thus, the scientific return of CCRSR will not be limited by the normal constraints on mass, power, size, etc, typical of spacecraft instruments. Indeed, some of the measurements made on Stardust samples were made using synchrotrons that were not only larger than the Stardust spacecraft, but were larger than the launch pad from which it left Earth!

Methods for collecting cometary particulates by a spacecraft inside a coma were developed under NASA sponsorship over a period of years in preparation for the CRAF mission. Vacuum-compatible viscid ("sticky") coatings and maze traps were both found effective. The predominant collector type for CCRSR will be maze traps, based on wire meshes and metal felts (available from multiple suppliers) which collect emitted particles by slowing them down through successive collisions, trapping them with >20% collection efficiency in the maze they have entered. Unlike Stardust, with its 6.1 km/s impact speed and aerogel collector, these particles will be collected under non-disruptive conditions (estimated at <0.2 km/s for 10 μm particles) by ultrapure materials. Molecular trapping by high-surface-area carbon can be used to collect larger molecules that exceed the mass range of the mass spectrometer.

The collector system would consist of passive surfaces that could be exposed or covered during separate collection periods so that samples collected at different times and from different cometary sources (for example, different jets) would be stored separately. The sampler would be capable of collecting a minimum of 10 independent samplings. There are several relatively simple ways to do this using either deployable paddles or a rotatable cover/collector plate with an off axis hole mounted over an underlying a second collection plate. Studies show that either system can be mounted on a deployable collector system very similar to the Stardust collector tray, requiring nothing more sophisticated than a few small, flight proven motors.

The camera suite would consist of a NAC and WAC (narrow- and wide-angle cameras) to provide initial navigation to the nucleus, high-resolution images at the surface (sub-meter pixels) and synoptic coverage of sporadic jet and other activity (Fig. 2). These cameras will: (i) support near nucleus navigation, (ii) map the comet nucleus at 1.0 m/pixel to characterize object shape, terrain roughness, local slopes, areas of outgassing, and determine object volume to better than 5%, (iii) track areas during perihelion passage to understand the processes that shape and evolve cometary terrain, and (iv) track the production, optical density, and evolution of comet jet activity. This includes tracking jets to their sources on the surface and characterizing the morphology of the source regions.

The dust flux monitor will measure the arrival and accumulation of dust particles to verify that sufficient sample material has been collected in any given sampling period and to plan for future sampling events. An instrument similar to the Grain Impact Analyzer and Dust Accumulator (GIADA) instrument on the Rosetta spacecraft [11] that would measure particles in the 3-1000+ micron size range over a velocity range of 1-100 m/sec could be used.

While it is possible that the dust collector may return some cometary volatiles trapped within collected particles (for example noble gases or H_2O in grains), the mission's principal means of studying cometary volatiles will be an onboard ion-neutral mass spectrometer. As a minimum, a mass range 1-150 amu would cover the range of the most abundant known or suspected cometary volatiles (H_2O, CH_3OH, CO_2, CO, NH_3, etc.) with sufficient resolution to make key isotopic measurements (D/H, C-, N-, and some O-isotope ratios). As an example instrument, the Neutral Gas and Ion Mass Spectrometer (NGIMS) flown on the CONTOUR Mission could measure the 1-300 mass range at mass resolutions of about 0.1 amu.

B.4. Mission Design

The CCRSR mission utilizes proven techniques inherited from Cassini, Stardust, and other deep space missions to return its samples from a comet. The basic mission design includes a launch and early cruise phase, an Earth flyby followed by a cruise to the comet, comet rendezvous and sampling activities made at intervals over a significant fraction of the comet's orbit, followed by return to Earth with the samples. In the ASRG-equipped variant, the ASRG would be jettisoned on the return trip into an intermediate orbit that does not intersect that of the Earth and the remainder of the trip would be powered by deployable solar panels. Figure 3 shows an image of how this would look in the specific case of a mission to Comet 46P/Wirtanen.

The spacecraft spends most of its time at the comet monitoring the nucleus and coma from a safe distance. During sampling events, the spacecraft maneuvers to a low altitude (~10 km) and then makes a predetermined pass across the targeted ejection event (for example, a specific jet). Measurements are made by the cameras, dust flux monitor, and mass spectrometer during each pass. The sampling system can make up to 10 independent samplings during different parts of the comet's orbit that collect from different source regions (different jets and inter-jet regions) and, if appropriate, unique events (for example, a cometary outburst).

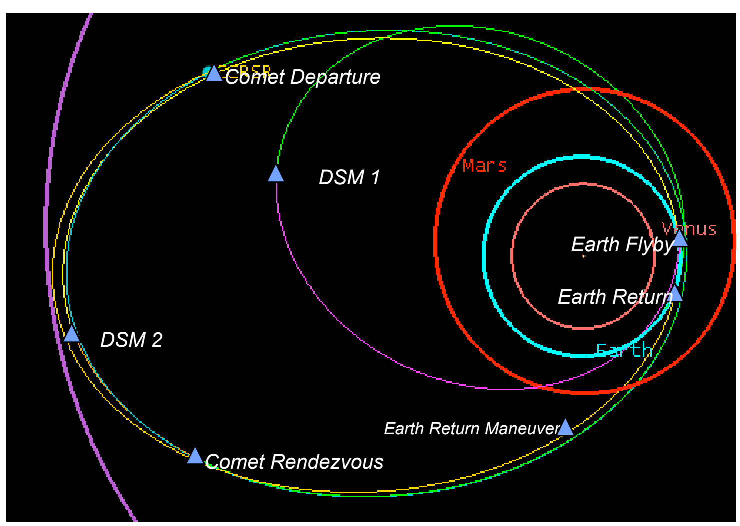


Figure 3. CCRSR uses a simple mission design that takes advantage of favorable orbital alignments.

B.5. The CCRSR Spacecraft and Subsystem Design

The overall spacecraft design and structural subsystems take advantage of the Lockheed-Martin SSC open architecture approach used on MGS, MCO, Odyssey, and MRO (Fig. 4). The specific design

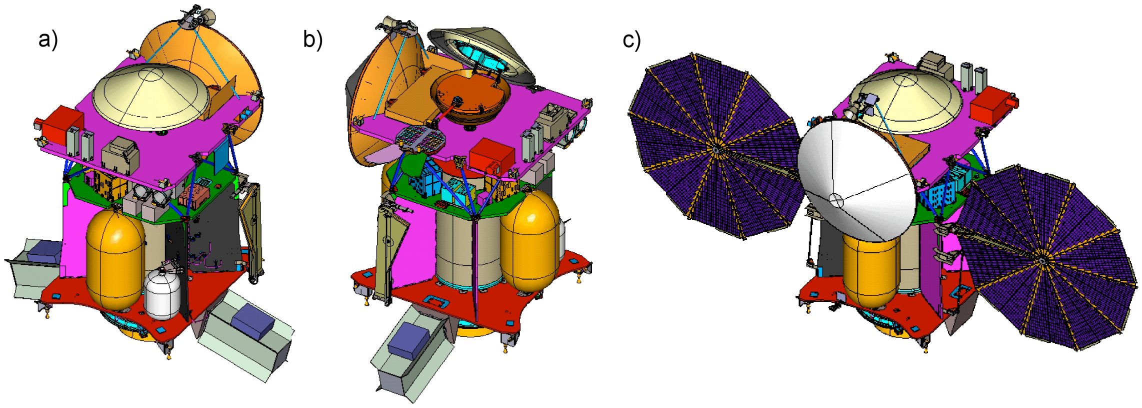


Figure 4. Spacecraft configurations: a) during launch and cruise configuration, b) during observation and sampling, c) after ASRG disposal prior to SRC return.

shares much in common with the Odyssey spacecraft including the propulsion, equipment and science bays.

Sample Return Capsule (SRC) - The SRC design builds on Stardust and Genesis designs, particularly in the heat shield, backshell, aerodynamic outer-mold line, passive-entry stability, parachutes, separation/spin mechanism, hinge and latch mechanisms, and backup locator beacon. As seen in Figure 5, the Genesis-sized heat shield is combined with the Stardust-sized back shell, to reduce the SRC ballistic coefficient and provide lower heating rates that are within capabilities of currently available test facilities. In addition, the SRC is mounted to the spacecraft with the same flight-proven mechanism used by Stardust to spin up and release its SRC.

REFERENCES AND CITATIONS

[1] Mannings V, Boss AP, Russell SS. eds, 2000. Protostars and Planets IV. Univ. Ariz. Press.
[2] Bottke WF Jr, Cellino A, Paolicchi P, Binel RP, eds. 2002. Asteroids III. Univ. Ariz. Press.
[3] Festou MC, Keller HU, Weaver HA, eds. 2004. Comets II. Tucson, AZ: Univ. Ariz. Press.
[4] Thomas PJ, Chyba CF, McKay CP, eds. 1996. Comets and the Origin and Evolution of Life. New York: Springer.
[5] Brownlee D, et al. 2006. Comet 81P/Wild 2 Under a Microscope. Science 314: 1711.
[6] Hörz F, et al. 2006. Impact Features on Stardust: Implications for Comet 81P/Wild 2 Dust. Science 314: 1716.
[7] Flynn GJ, et al. 2006. Elemental Compositions of Comet 81P/Wild 2 Samples Collected by Stardust. Science 314: 1731.
[8] McKeegan KD, et al. 2006. Isotopic Compositions of Cometary Matter Returned by Stardust. Science 314: 1724.
[9] Sandford SA, et al. 2006. Organics Captured from Comet 81P/Wild 2 by the Stardust Spacecraft. Science 314: 1720.
[10] Zolensky ME, et al. 2006. Mineralogy and Petrology of Comet 81P/Wild 2 Nucleus Samples. Science 314: 1735.
[11] Colangeli, L., et al. 2007. GIADA: The Grain Impact Analyzer and Dust Accumulator for the Rosetta Space Mission. Adv. Space Res. 39: 446.

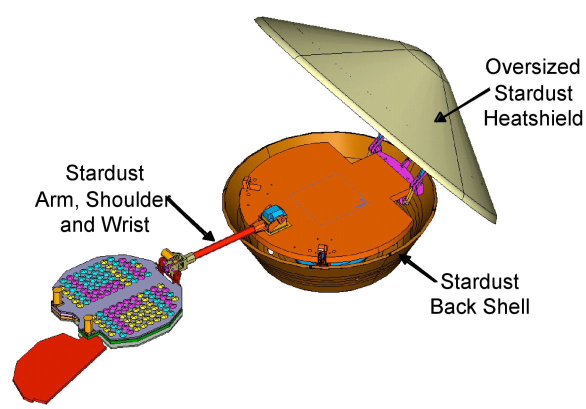


Figure 5. The SRC design draws on experience with Stardust and Genesis. This image shows the deployable paddles collector design.