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Introduction: Atmospheric Entry of the Stardust Sample Return Capsule

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IN THIS issue of the *Journal of Spacecraft and Rockets* is a collection of articles pertaining to the atmospheric entry of the Stardust SRC. Each article presents and/or leverages some aspect of three sources of flight information: the recovered SRC thermal protection system, airborne observation of the entry using instruments that provide spectral resolution of the hot SRC and shock layer gasses, and radar signature during the terminal descent stage. As an introduction to this special edition, the Stardust SRC is described, followed by a broad description of the flight data sources. Specific aspects of the flight data are described in greater detail in the articles.

In the early morning of 15 January 2006, the Stardust Sample Return Capsule (SRC) successfully delivered its precious cargo of cometary ejecta particles to the awaiting recovery team at the Utah Test and Training Range (UTTR). The SRC returned to Earth at 12.8 km/s (inertial): the fastest human-made object to traverse our atmosphere and only the second NASA superorbital velocity entry since the Apollo Program (the previous being the Genesis SRC). In addition to the excitement that comes with the rarity of obtaining extraterrestrial material for scientific study, it was a remarkable event in entry physics. At this entry speed, the atmospheric gas in the shock layer preceding and surrounding the SRC was dissociated and glowing hot, so hot that preflight analysis predicted that roughly 10% of the heat flux to the body at peak heating would be due to radiant energy from the shock layer. In addition, the heatshield thermal protection system (TPS) was the first use of a mission enabling NASA-developed lightweight material (phenolic impregnated carbon ablator, or PICA) that manages the incident heat flux by means of ablation. The ablation products were mixed into the shock layer thereby creating a complex, and remarkable, fluid-material interaction at very high energy. Unfortunately, the SRC was not instrumented and, as a consequence, there are no time-resolved direct measurements of the state of the aeroshell, e.g., acceleration, temperature, pressure, etc. However, an auxiliary mission to observe the entry from an airborne platform was successfully executed. These data, in combination with preflight specifications, in-space navigation, terminal descent radar, and recovered hardware, constitute a rich source of evidence with which to assess the performance of the entry system.

I. Sample Return Capsule Description

The Stardust SRC was built by the Lockheed Martin Space Systems Company. The aeroshell was composed of two primary components: [1] a 60 deg sphere-cone forebody heatshield and a 30 deg truncated cone backshell (see Fig. 1). The width at maximum diameter was 0.827 m. The flight path was nominally ballistic (nonlifting trajectory) with a ballistic coefficient of $\sim 60\ \mathrm{kg/m^2}$. The expected upper bound of the heating environment was a peak heating of $\sim 1200\ \mathrm{W/cm^2}$ at the forebody stagnation point and a heat load of $\sim 36\ \mathrm{kJ/cm^2}$. Of the total incident heat flux, about 10% was expected to be from shock layer radiation at the time of peak heating.

The main thermal component of the Stardust forebody heatshield was PICA [2] material, developed at NASA Ames Research Center under the lightweight ceramic ablator development program in the 1980s. It consisted of a rigid carbon fibrous substrate infiltrated with phenolic resin yielding a TPS with good ablation and pyrolysis behavior. In addition, PICA had the advantages of low density (~ 0.27 g/cc) coupled with efficient ablative capability at high heat fluxes, making it an enabling technology for the Stardust mission. In comparison to conventional high-density carbon phenolic TPS solutions, PICA's thermal conductivity was substantially lower. The PICA TPS was cast-molded as a single piece by Fiber Materials Incorporated.

The backshell TPS was super lightweight ablator [3] (SLA-561V), a Lockheed Martin ablative TPS material developed in the 1960s. This material has substantial flight heritage: it was used on the forebody heatshields of all NASA missions to Mars (e.g., Viking, Pathfinder) and on portions of the Shuttle external tank. SLA-561V consisted of an ablative component packed in a honeycomb core. The core was prebonded to the substructure allowing construction of a large component and efficient bond verification.

The entry, descent, and landing of the SRC occurred as depicted in Fig. 2. Upon release from the spacecraft bus, the SRC was spun to approximately 16 rpm. The spinning aeroshell provided unguided aerodynamic stability and thermal protection as it decelerated to low supersonic Mach numbers [4,5]. Near Mach 1.4 and ~ 32 km, a drogue chute was deployed to provide dynamic stability as the baseline SRC became increasingly unstable approaching transonic speeds. At Mach 0.16 and 3.3 km the descent parachute was deployed [6]. The SRC descended to the ground under chute.

II. Flight Data Sources

A. Airborne Observation

The flight path from the Pacific Ocean to UTTR provided viewers in California, Nevada, and Utah a visually stunning meteor sighting, a meteor who's timing and flight path were quite predictable. Figure 3 shows the SRC transit as seen from Wendover, Utah. Leveraging the methodologies and personnel from the meteor observation community, a team of researchers imaged the SRC entry aboard the NASA DC-8 airborne observatory [7]. At SRC entry, the airplane was at 39 kft positioned within 4 miles of the prescribed, preferred target view location in Nevada just outside the western boundary of UTTR. The incoming SRC was first acquired approximately 18 s after atmospheric interface and tracked for approximately 60 s, an observation period that was roughly centered in time around predicted peak heating. The radiative signal from the SRC and surrounding shock layer gasses were measured by 15 of 18 instruments that had various combinations of spectral range, spectral resolution, and temporal resolution (note that there was no spatial resolution of the SRC; it appeared to all the cameras as a point source). The data were assessed to be of good quality and sufficient to address all observation objectives: absolute radiance, spectral resolution of shock layer emission, and wake train evolution. Further details of the observation campaign flight, instrument suite, and acquired data can be found in [7]. In addition to the instruments aboard the aircraft, there were complementary ground observations from sites along the track.

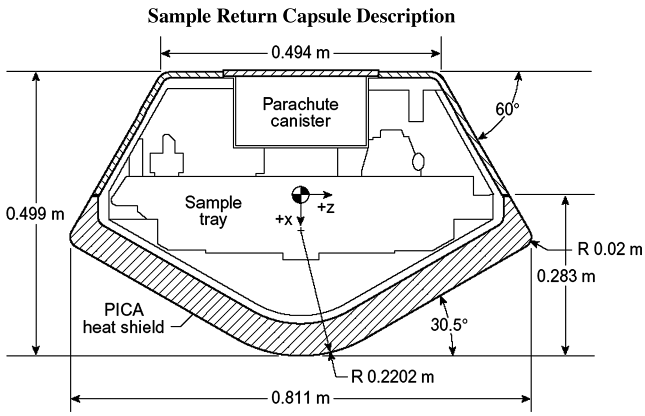

Fig. 1 Stardust SRC.

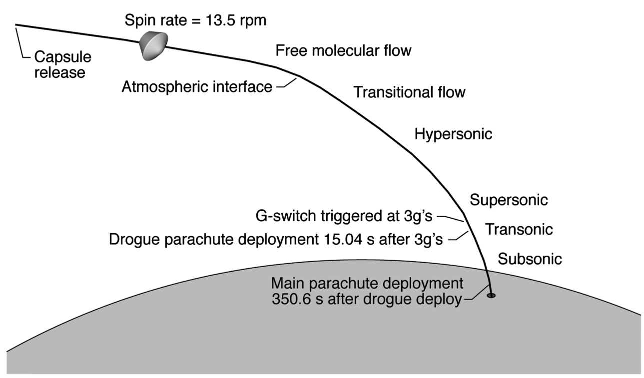

Fig. 2 Nominal stardust entry, descent, and landing sequence.

Fig. 3 Photograph of SRC transit from Wendover Airfield, Utah with star map overlay (courtesy Bruce Fischer).

B. Terminal Descent Radar

The incoming SRC was acquired before drogue chute deployment by ground radar stationed at UTTR at approximately Mach 2 and 35 km. The SRC was tracked through drogue chute deployment, main chute deployment, and descent under canopy, a total duration of ∼11.5 min. From range and timing data, the vehicle velocity and absolute position is known through that time period.

C. Recovered Hardware

As a consequence of design requirements for safe and intact return of the sample collection array, the SRC landing was a fairly benign event to the aeroshell. Based on imprints in the dirt and marks on the aeroshell, it is surmised† that the SRC first impacted on the forebody aeroshell nose approximately 15° from the symmetry axis. It then bounced a total of four times. After the last small bounce, the SRC ended up on its rim, at which time it rolled on its edge in a weaving manner downwind for a total of about ∼25 m. Near the end of the roll, the SRC had slowed enough that several times it flopped down on the side of the backshell briefly before coming back up to roll on the rim a little further. Finally, the SRC tipped onto the side of its backshell for good, rolled in almost a complete circle, and came to rest on its side. Figure 4 shows the SRC in its final resting position. The initial impact location near the nose and the edge bounce location are evident. Also seen in the photo are parachute bridles extending from the rear. The parachute was released at the riser by a cutter triggered by the deceleration at impact. The parachute canister lid that forms the rear enclosure of the backshell would have come down at another location and was not found.

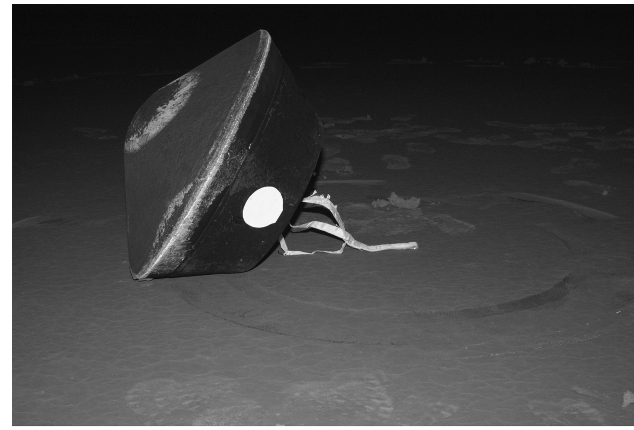

Fig. 4 Photograph of SRC after landing and before recovery (courtesy Scott Sandford).

The aeroshell was lifted whole and transported to a processing facility at UTTR [8]. In a Class 10000 clean room, the SRC was separated into its three primary structural pieces: the forebody heatshield, backshell, and sample return canister. The forebody heatshield component extended beyond the maximum diameter of the SRC and comprises about one quarter the length of the aft-facing flank. The sample canister was attached to the avionics deck within the forebody aeroshell component. The sample canister was separated from the heatshield and stored in a special gaseous N_2 purged container. The heatshield and backshell were placed in individual, unpurged containers. All hardware, including the three major components of sample canister, heatshield, and backshell, were then transported to Johnson Space Center (JSC) on 17 January 2006. At JSC, the sample canister was moved to the class 100 Stardust cleanroom and opened. Sample recovery and analysis activities were then begun by the Stardust science team. The other components (heatshield and backshell) were curated as space exposed hardware in the space exposed hardware cleanroom.

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Guest Editors