

PLUME COLLECTION STRATEGIES FOR ICY WORLD SAMPLE RETURN. M. Neveu¹, D. P. Glavin², P. Tsou³, A. D. Anbar¹, P. Williams¹. ¹Arizona State University, Tempe, AZ, USA, ²NASA Goddard Space Flight Center, Greenbelt, MD, USA, ³Sample Exploration Systems, La Cañada, CA, USA. Email: mneveu@asu.edu.

Introduction: Three icy worlds in the solar system display evidence of pluming activity. Water vapor and ice particles emanate from cracks near the south pole of Saturn's moon Enceladus [1]. The plume gas contains simple hydrocarbons that could be fragments of larger, more complex organics [2]. More recently, observations using the Hubble and Herschel space telescopes have hinted at transient water vapor plumes at Jupiter's moon Europa [3] and the dwarf planet Ceres [4]. Plume materials may be ejected directly from possible sub-surface oceans, at least on Enceladus [5]. In such oceans, liquid water, organics, and energy may co-exist, making these environments habitable. The venting of habitable ocean material into space provides a unique opportunity to capture this material during a relatively simple flyby mission and return it to Earth [6]. Plume collection strategies should enable investigations of evidence for life in the returned samples via laboratory analyses of the structure, distribution, isotopic composition, and chirality of the chemical components (including biomolecules) of plume materials.

Here, we discuss approaches for the collection of dust and volatiles during flybys through Enceladus' plume, based on *Cassini* results and lessons learned from the Stardust comet sample return mission. We also highlight areas where sample collector and containment technology development and testing may be needed for future plume sample return missions.

Enceladus Plume Composition and Density: Enceladus' plume gas, characterized by *Cassini* instruments, is composed of 90% water, 5% CO₂, and 4% CO or N₂, with trace (< 1%) C₁-C₆ hydrocarbons, H₂CO, and HCN [2]. The plume also contains Na and K [7], and seems to feed silica grains to Saturn's E-ring [8]; these species may be leached from Enceladus' core. Model estimates, based on plume composition [2,5] and density [9], suggest that during a plume fly-through at 20 km altitude could allow the capture of about 10⁻³ g of ice and 10⁻⁵ g of silicate minerals and organics per m² of collector surface area. This estimate is valid for particles > 0.2 μm, the size threshold for measuring composition [2]; additional mass may be captured as nano-sized grains [10,11]. If the abundance of glycine is similar to that of H₂CO (0.3 wt%) [2], 100 nmol glycine per m² would be collected in a 20 km flyby. This is similar to glycine concentrations measured on Stardust foils exposed to comet Wild 2 [12].

Sampling Strategy and Collector Design: Lessons learned from Stardust can help guide sampling strategies and collector designs. These are influenced by three considerations, detailed below.

1- *Collect enough plume material to allow biosignature investigations on Earth.* This requires several

low-altitude flybys using a collector that contains multiple surface adsorbents and substrates optimized to capture and retain water, silicate grains, biomolecules and other organics, and noble gases.

A compelling substrate is silica aerogel, both flight-proven and exceptional at capturing and preserving silicate grains and volatile organics [13], including amino acids and amines [14,15]. Other substrates for refractory particles are aluminum, gold, or stainless steel surfaces. On such solid surfaces, ice grains explode upon impact and entrained biomolecules are volatilized and able to deposit on secondary collector surfaces [16]. Such secondary collectors present major analytical advantages. They can be configured for direct, robotic insertion into mass spectrometers upon return, minimizing exposure to terrestrial contaminants. They can also be hydrophobically-patterned so that the diffuse capture layer of biomolecules and organics can be dissolved and concentrated into small spots prior to analysis.

Capture assemblies can be exposed to various samples (e.g. Enceladus plume and Saturn E-ring) during multiple flybys via a rotating cover (Fig. 1).

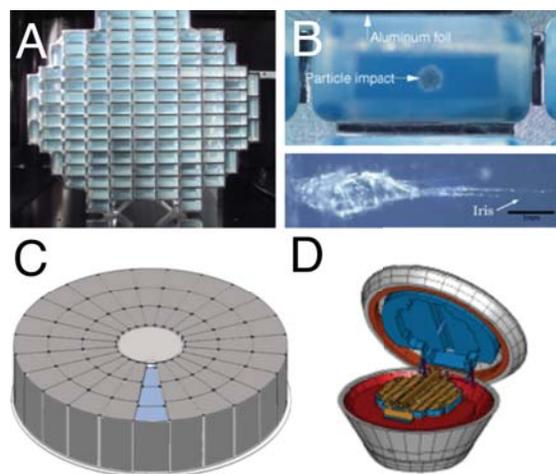


Figure 1. A. Stardust collector with aerogel cells separated by aluminum foil ribs. B. Cross section of a comet dust impact track. C. Rotating collector tray to expose different substrates for multiple flyby samplings. D. Return to Earth via a Stardust-like capsule. Image NASA/JPL-Caltech/U. Washington.

2- *Minimize sample damage during capture.* Here, the capture velocity is a key factor. As a particle's kinetic energy is converted into heat upon impact, samples may be altered or destroyed. Indeed, laboratory impact experiments of meteorite particles in aerogel at 6 km/s (Stardust encounter speed: 6.1 km/s) showed chemical transformations of indigenous polycyclic

aromatic hydrocarbons due to impact heating [17]. However, cometary glycine was identified in samples of aerogel and foil returned to Earth by Stardust [12].

Trajectory simulations have shown that a spacecraft in Saturn orbit with gravity assists from Titan can achieve Enceladus plume encounter speeds < 2 km/s [6]. Such low velocities may ensure the survival of organics and biomolecules: experiments have shown that 95% of hexapeptide ions survive impact at 3.5 km/s on a surface coated with a self-assembled long-chain thiol monolayer, and that some parent ions and significant structural information survive collisions at 4.6 km/s [18] (Fig. 2). Ice-encased polypeptides and short DNA oligomers (10-mers) survive collisions with metal targets in vacuum at speeds that vaporize ice entirely [16]. Stearic acid and anthracene trapped in frozen dimethylsulfoxide survive 4 km/s impacts [19]. Thus, complex organics in a frozen matrix may be captured relatively intact during a < 4 km/s flyby.

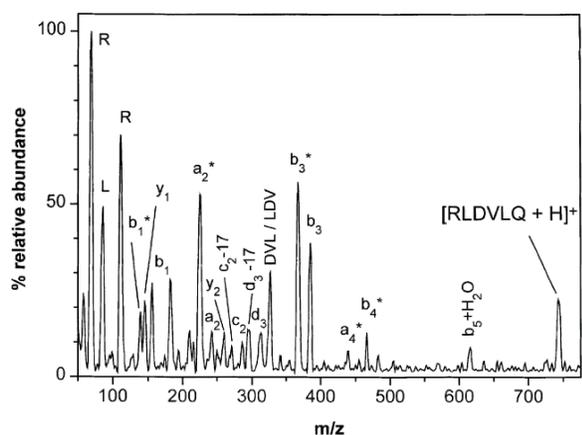


Figure 2. Mass spectrum of the polypeptide ion RLDVLQ (Arg-Leu-Asp-Val-Leu-Gln) after impact onto a monolayer of octadecanethiolate on gold at 4.6 km/s, showing survival of the parent ion [18].

3- Minimize terrestrial volatile and organic contributions, including spacecraft outgassing products, to the plume sample. This requires cleaning the collector and return capsule, and protecting them from recontamination. To help discriminate between plume material and terrestrial contamination, witness materials exposed to the spacecraft environment during all phases of the mission, but not to the plume, must be included in the collector and capsule design.

Stardust sample investigations were complicated by a high background of terrestrial carbon (Si-CH₃ groups) and organics (including amino acids and amines) within the aerogel itself [17]. Reducing the aerogel density from 10 to 2 mg cm⁻³ would reduce this background. (Coupled with a lower plume encounter speed, this would lead to a 50-fold reduction in impact energy.) However, aerogel is intrinsically a high-background material due to its large internal surface area, which determines the abundance of atmos-

pheric contaminants on any material. Moreover, the recovery of trapped samples is difficult, because aerogel is typically hydrophobic and cannot be heated to temperatures high enough to completely remove organics without damaging the aerogel structure, resulting again in high background levels. In contrast, materials with high depth/cross-section ratios, such as honeycomb metal or graphite, should be easier to outgas. On metallic surface collectors, organic contamination is even more easily removed either chemically or thermally. Regardless of the material, collector backgrounds could be reduced by outgassing to space prior to sample capture, both by heating using the onboard power supply and by exposure to solar radiation.

Loss of volatiles can occur after sample return. The Stardust collector was stored at room temperature in an ISO Class 5 cleanroom at NASA's Johnson Space Center (JSC). Analyses of Stardust foils at NASA's Goddard Space Flight Center have revealed that their glycine levels dropped 6 to 10-fold over 1000 days during storage at JSC. It may be that volatile glycine precursors (e.g. formaldehyde and aminoacetonitrile) were lost from the foils. To avoid a similar loss of volatiles returned from icy world plumes, the collector should be maintained below the *in situ* sample temperature at capture. Active collector cooling and phase change materials inside the capsule could maintain cold temperatures during Earth entry. As a cold sample collector would act as a cold trap during reentry, the returned sample tray should be shielded from atmospheric volatiles and organics, as well as from products of ablation and outgassing of the return capsule.

Conclusion: Plume collection strategies must collect enough sample, minimize damage upon collection, and minimize terrestrial contamination. Lessons learned from Stardust and laboratory experiments suggest that the collection concepts discussed in this abstract could enable biosignature investigations on samples returned from icy world plumes.

References: [1] Spencer J. R. et al. (2006) *Science* 311, 1401. [2] Waite J. H. et al. (2009) *Nature* 460, 487. [3] Roth L. et al. (2013) *Science* 343, 171. [4] Küppers M. et al. (2014) *Nature* 505, 525. [5] Porco C. et al. (2014) *AJ* 148, 45. [6] Tsou P. et al. (2012) *Astrobiology* 12, 730. [7] Postberg F. et al. (2011) *Nature* 459, 1098. [8] Postberg F. et al. (2013) *EPSC* abstract 704. [9] Spahn F. et al. (2006) *Science* 311, 416. [10] Jones G. H. et al. (2009) *GRL* 36, L16204. [11] Hill T. W. et al. (2012) *JGR* 117, A05209. [12] Elsila J. et al. (2009) *Meteoritics Planet. Sci.* 4, 1323. [13] Tsou P. et al. (2003) *JGR* 108, E108113. [14] Sandford S. A. et al. (2006) *Science* 314, 1720. [15] Glavin D. P. et al. (2008) *Meteoritics Planet. Sci.* 43, 399. [16] Aksyonov S. A., Williams P. (2001) *Rapid Comm. Mass Spec.* 15, 2001. [17] Sandford S. A. et al. (2011) *Meteoritics Planet. Sci.* 43, 399. [18] Gu C. et al. (1999) *Anal. Chim. Acta* 397, 247. [19] Burchell M. J. et al. (2014) *Astrobiology* 14, 473.