THE CAESAR NEW FRONTIERS MISSION: 2. SAMPLE SCIENCE. D.S. Lauretta[1], S. W. Squyres[2], S. Messenger[3], K. Nakamura-Messenger[3], T. Nakamura[4], D. P. Glavin[5], J. P. Dworkin[5], A. Nguyen[6], S. Clemett[6], Y. Furukawa[4], Y. Kimura[7], A. Takigawa[8], G. Blake[9], T. J. Zega[1], M. Mumma[5], S. Milam[5], C. D. K. Herd[10] and the CAESAR Project Team. [1]University of Arizona, Tucson, AZ, USA. [2]Cornell University, Ithaca, NY, USA. [3]NASA Johnson Space Center, Houston, TX, USA. [4]Tohoku University, Sendai, Miyagi Prefecture, Japan. [5]NASA Goddard Space Flight Center, Greenbelt, MD, USA. [6]JETS, NASA Johnson Space Center, Houston, TX, USA. [7]Hokkaido University, Sapporo, Hokkaido, Japan. [8]Kyoto University, Kyoto, Kyoto Prefecture, Japan. [9]California Institute of Technology, Pasadena, CA, USA. [10]University of Alberta, Edmonton, AB, Canada. Email: lauretta@lpl.arizona.edu

Introduction: Comets are time capsules from the birth of our Solar System that record presolar history, the initial stages of planet formation, and the sources of prebiotic organics and volatiles for the origin of life. These capsules can only be opened in laboratories on Earth. CAESAR's sample analysis objectives are to understand the nature of Solar System starting materials and how these components came together to form planets and give rise to life [1]. Examination of these comet nucleus surface samples in laboratories around the world will also provide ground truth to remote observations of the innumerable icy bodies of the Solar System.

Target Comet 67P/Churyumov-Gerasimenko: Every comet has a unique history, and past missions have revealed considerable diversity among comets. The Jupiter-family comet (JFC) 67P/Churyumov-Gerasimenko (67P) is the CAESAR target. Its selection was based on its favorable orbital geometry for a rendezvous and the low-risk posture enabled by ESA's Rosetta mission. The Philae surface lander, which bounced across the surface before coming to rest, provided important constraints on the physical and chemical properties of the comet surface materials. As a result, 67P is *the best-characterized comet*. Another critical advantage of 67P is its dynamical history: a Jupiter encounter in 1959 lowered its perihelion distance from 2.74 to 1.28 AU, and typical perihelion values for the 10,000 years before that were 2-5 AU [2]. 67P may, therefore, be less altered by sublimation-driven processes in the inner Solar System than many JFCs, making it a particularly well-suited time capsule.

Conflicting Hypotheses of Cometary Origins: The variable volatile chemistry, isotopic compositions and mineralogy among comets suggest they record different formation environments. Many researchers view comets as unprocessed assemblages of interstellar matter [3,4]. Others suggest that comets are composed of protoplanetary disk condensates or processed materials [5,6]. Alternatively, some comets may be rubble piles of fragments from catastrophically disrupted massive objects that underwent planetary-scale processes such as volcanism, differentiation, and surface modification [7].

Spacecraft mission results also give conflicting views of comet origins. Stardust-mission samples from comet 81P/Wild 2 showed that the outer Solar System was not an isolated refuge but instead contained refractory inclusions and chondrule fragments from the hot inner nebula [6]. In sharp contrast, some of Rosetta's findings are consistent with an interstellar or strictly outer Solar System origin. For example, volatiles in the coma of 67P have signatures suggesting formation at ≤30 K, seemingly unchanged for billions of years [7].

Rosetta also showed that comets are even more enigmatic than once thought. 67P's bilobate shape suggests that this comet may have formed by a gentle collision between km-sized cometesimals and is a remnant from the dawn of the Solar System. The alternative is that 67P evolved through collisions and its final shape is a result of its last significant impact. In this case, 67P may be a rubble pile of fragments from collisions between larger trans-Neptunian objects. As a result of this wide range of possible histories, we focus the CAESAR sample science investigation on the possible origins of comets in general and 67P in particular (Table 1).

Sample Types: The distinctly different views of cometary origins from the Stardust refractory material vs. the Rosetta volatile analysis provide the rationale for returning both solid and gaseous samples. The basic properties of cometary solids – texture, bulk mineralogy and chemistry – have bearing on every hypothesis and give essential context to more focused measurements. These studies will allow for comparison of 67P with 81P, IDPs, meteorite components, OSIRIS-REx samples, Hayabusa2 samples, and solar composition, providing ground truth to decades of research and exploration. First order observations will reveal if 67P is a primordial fossil from the early Solar System or a fragment from a disrupted KBO. Detailed investigation will elucidate the distinct history of the solid materials.

CAESAR's return of volatiles from 67P will give an unprecedented view of the most ephemeral of Solar System starting materials. Analyses of these components will yield far higher isotopic precision and orders-of-magnitude lower detection limits than are possible with spacecraft instrumentation. The precision and sensitivity of cometary volatiles afforded by laboratory study will yield significant advances in disciplines ranging from molecular cloud chemistry to evolution of Solar System volatile reservoirs and the first steps of prebiotic organic synthesis.

The inconsistent and variable isotopic measurements of cometary coma H_2O underscore the need for an independent measurement of ice directly from the nucleus surface. Precise measurements of H and O isotopes in H_2O are necessary to determine whether JFCs like 67P could have contributed a significant fraction of Earth's water. Measurement of D/H in the bulk and molecular organic fractions are needed to constrain the delivery of D and H from those components [8].

Comets and asteroids delivered organic matter that may have supported the emergence of life on Earth. Meteorites contain nucleobases, amino acids, carboxylic acids and polyols that may be products of aqueous chemistry. Experiments suggest purines such as adenine and guanine formed by ammonium cyanide chemistry in asteroids. Nucleobases, amino acids, and fatty acids may have formed from HCN, aldehydes and ketones in a similar setting. Sugar derivatives such as sugar acids and sugar alcohols are observed. Comets have been proposed to be dominant sources of Earth's organic matter, but few prebiotic compounds are observable remotely. The large mass to be delicately collected, separated, and returned by CAESAR will enable the first robust characterization of prebiotic organics in a comet.

Considering the wealth of knowledge gleaned from less than a milligram of material returned from 81P by Stardust, CAESAR's return of ≥80 g of both non-volatile and volatile samples from a well-characterized comet will bring a leap forward in our understanding of Solar System history. Testing these hypotheses requires non-volatile and volatile sample analyses that can only be carried out in terrestrial laboratories. After completion of the CAESAR sample analysis program, only the most robust hypotheses will remain.

Samples for the Community: We based CAESAR's science investigation on existing capabilities and instrumentation. We can achieve our sample analysis goals using current technologies for coordinated sample analyses that link macroscopic properties of the comet with microscale mineralogy, chemistry, and isotopic studies of volatiles and solids. However, since CAESAR samples will be returned 20 years from now, future researchers will address these fundamental science goals using ever more capable instruments and new scientific insights, providing an invaluable scientific resource for the worldwide planetary science community for generations to come.

References: [1] S.W. Squyres *et al.* (2018) 49th LPSC. [2] L. Maquet (2015) *Astron. & Astrophys.* **579**, A78. [3] J.M. Greenberg (1982) in *Comets* (ed. L.L. Wilkening), UofA Press, Tucson, AZ, 131-163. [4] G. Notesco and A. Bar-Nun (2005) *Icarus* **175**, 546–550. [5] J.I. Lunine et al. (1991) *Icarus* **94**, 333–344. [6] D. Brownlee (2014) *Annu. Rev. Earth Planet. Sci.* **42**, 179–205. [7] M. Rubin *et al.* (2015) *Science* **348**, 232–235. [8] Alexander *et al*. (2012) *Science* **337**, 721-723.

Table 1. CAESAR Sample Science Traceability Matrix.

Testable Hypotheses	Observables from Solid Sample and Volatile Sample / Observables from Solid Sample
Interstellar Medium to Protoplanetary Disk Transition	
67P contains a greater abundance and diversity of circumstellar grains and molecules than asteroids sampled by meteorites.	Crystallography, elemental and isotopic compositions of mineral and organic grains; molecule-specific isotopic ratios; noble gases
67P contains volatile elements, ices and organic molecules that were trapped during formation of grain mantles in the ISM or outer protoplanetary disk.	Isotopic and chemical compositions of volatile elements, organics, and noble gases (GCS). Isotopic compositions of noble gases in non-volatile samples
67P contains refractory organic compounds that formed in cold molecular clouds and the outermost protosolar disk.	Isotopic and chemical compositions of refractory organic molecules & carbonaceous grains; Isotopic, chemical and structural properties of macromolecular material.
H_2O and CO in 67P retain evidence of O isotopic fractionation from photochemical self-shielding.	Oxygen isotopic compositions of H_2O and CO
Protoplanetary Disk	
67P contains high-temperature materials, such as chondrules, CAIs, and silicates that formed across the Solar System.	Mineralogy, chemistry, and isotopic compositions of chondrules, CAIs, metals, sulfides, crystalline and amorphous silicates
67P contains complex refractory organics from the hot, inner regions of the protoplanetary disk.	Textures, chemistry, and isotopic compositions of refractory organics
67P is a primordial fossil that retains largely unaltered signatures from the protoplanetary disk epoch.	Textures, mineralogy, crystallography, and isotopic compositions of grains and organics. H and O isotopic ratios of hydrated minerals and H_2O
Geological and Dynamical Evolution	
67P is a collisional remnant of a larger planetesimal that underwent internal heating, partial differentiation, sublimation and recondensation, outgassing, and hydrothermal alteration.	Crystallography, petrology, mineral textures, labile element abundances, mineralogy, trace element profiles, H and O isotopic measurements of hydrated minerals and H_2O
Jupiter family comets delivered a substantial fraction of water to Earth.	H and O isotopic measurements of H_2O, H isotopic measurements of organics
67P contains prebiotic organic compounds that may have contributed to the origin of life on Earth.	Volatile and non-volatile organic molecule abundances, isotopic ratios, and chirality, mineralogical constraints for aqueous alteration
67P surface materials record processes of tidal disruption and reaccumulation, resurfacing, and mass wasting.	Space weathering rims, mineral microstructures, IR spectra, noble gas abundances and isotopes