SAMPLE RETURN FROM ALL ACROSS THE SOLAR SYSTEM: A KECK INSTITUTE FOR SPACE STUDIES STUDY PROGRAM. M. Choukroun[1], J.M. Eiler[2], H. Ishii[3], A. Adeloye[4], J.C. Aponte[5], L. Borg[6], M.E. Brown[2], D.L. Buczkowski[7], V. Forero[8], A. Freeman[1], P.A. Gerakines[5], A.E. Hofmann[1], J.M. Jackson[2], R.R. Karimi[1], Y. Liu[1], J.I. Lunine[1], K.J. Meech[3], A. Meshoulam[2], K.E. Miller[9], A. Mojarro[5], M. Neveu[5], R.C. Ogliore[10], C.A. Raymond[1], L.M. Saper[1], L. Shiraishi[1], S. Tachibana[11], F.L.H. Tissot[2], H. Yabuta[8], T.E. Yap[2], M. Zolensky[12], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]California Institute of Technology, [3]University of Hawai'i at Manoa, [4]University of Texas, Austin, TX, [5]NASA Goddard Space Flight Center, [6]Lawrence Livermore National Laboratory, [7]Applied Physics Laboratory, John Hopkins University, [8]Hiroshima University, [9]Southwest Research Institute, [10]Washington University in Saint Louis, MO, [11]University of Tokyo, [12]NASA Johnson Space Center.

Introduction: The planetary science community has fully entered the era of analyzing returned samples from planetary bodies, following the recent successes of the Japan Aerospace eXploration Agency (JAXA) *Hayabusa* [e.g., 1] and *Hayabusa2* [e.g., 2] missions, as well as NASA's *Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer* (*OSIRIS-REx*) mission [e.g., 3]. The Origins, Worlds and Life (OWL) Planetary Decadal Survey for the current 2023-2032 decade [4] furthermore placed a very strong emphasis on sample return missions. Mars Sample Return is considered the highest priority mission for this decade. Sample return missions from the surface of a comet nucleus, and from Ceres, are among targets for upcoming rounds of *New Frontiers* missions.

In this study, we evaluate the science case for the analysis of returned samples from most foreseeable places in the Solar System, consider the feasibility of accessing these bodies, and the state of development of technologies needed to maximize the science return from these missions. A first workshop took place in September 2024, and a second workshop will take place in late February 2025. This abstract reports on the first workshop, while the study outcomes following both workshops will be presented at the conference.

Notional mission architecture: In this study, we used the same baseline architecture as described in [5], with a Starship launch vehicle refueled in low-Earth orbit, a spacecraft equipped with either nuclear electric propulsion (NEP) or nuclear thermal propulsion (NTP). This architecture enables the launch of spacecraft with sufficient propulsive power to reach previously unforeseen destinations with enough resources to carry a landed sampling platform, *and* return samples back to Earth within a much shorter timespan than previously achievable [5].

Scientific priorities for sample return missions: Three primary areas of broad interest for sample return missions from across all solar system targets emerged during discussions at the first workshop: 1) origins of these targets, i.e. characterize the primordial materials that they accreted and decipher the condition(s) and location(s) within the protosolar disk from which they originated, 2) potential for emergence and sustenance of life, in particular directly on/within ocean worlds, and delivery of prebiotic materials to the inner solar system, and 3) origin, distribution, and evolution of icy materials, from permanently shadowed areas on Mercury and the Moon, to polar caps on Mars, to comets and outer Solar System objects. These priorities are broadly consistent with the OWL Decadal Survey.

Science objectives and measurements: In the first workshop, all solar system bodies (or classes of bodies) were considered. We first developed dedicated science objectives for sample return missions to each target, taken directly from the Strategic Research elements delineated in the OWL Decadal Survey when applicable, or inspired by them. We discussed the analytical measurements that would need to be conducted on samples from each target (or target type) to accomplish these objectives.

High-level sample requirements: We then used the science objectives and analytical measurements to derive sample requirements, including sample amounts, specific sampling location(s) if applicable, possible need to preserve stratigraphic information in the sample(s), and sample integrity preservation considerations. As expected, a particularly challenging area of sample integrity preservation is cold to cryogenic conditions.

Targets of interest: One of the primary goals of this study was to evaluate all planetary bodies that could be accessed for sample return with the notional mission architecture described in [5]. Giant planets are not extensively discussed, as the critical information they could provide towards OWL Decadal Survey questions would require compositional data from depths that can only be reached by high-pressure probes.

Mercury and Venus: Mercury and Venus are unrepresented in meteorite collections. A companion presentation [6] elaborates on scientific objectives and measurements. With the notional mission architecture considered, samples could be returned from Mercury's surface, or Venus' atmosphere, however the surface of Venus is inaccessible [5].

The Moon and Mars: The Earth's Moon and Mars are already the targets of dedicated sample return programs (*Artemis, Mars Sample Return*). Beyond these programs, areas of interest pertained to refining our understanding of the hydration state of the lunar interior, conduct precise dating of ancient crater on Mars to refining crater chronology, and for both bodies, return cryogenic polar ice deposit samples to understand their origin and climatic evolution or volatile migration.

Asteroids: As demonstrated by recent missions, many near-Earth asteroids can be accessed with much smaller mission architectures that the one considered. Potential new targets of interest that a large architecture could enable include the Jupiter Trojans, large planetesimal remnants, L-type, enstatite-rich, and differentiated stony asteroids.

Ocean Worlds: Ceres, as a relic ocean world, is a target of high interest and already considered for sample return with a smaller architecture that could be developed within *New Frontiers*. A larger architecture may enable a cold or cryogenic sample return. Europa and Enceladus are targets of choice for existing in-situ habitability and/or life-searching mission concepts (*Europa Lander*, *Enceladus Orbilander*). A sample return mission could follow these potential missions. Titan would also be a high-value target for sample return, following the *Dragonfly* mission. Planetary protection is an area of primary concern for returned samples from ocean worlds and needs further evaluation.

Io: Returned samples from Io could inform its formation and history. The mission architecture considered here could enable a sample return from Io's surface. A companion presentation [7] elaborates on scientific measurements priorities for Io, including an alternative architecture that only samples its plumes.

Comets: Comets have been targets of choice for sample return mission concepts (including cryogenic) for decades. Although a surface sample can be returned from a Jupiter-Family Comet with a *New Frontiers* mission, other comet families (Manx, Helley-type, Oort Cloud comets) require larger architectures. The architecture considered here could potentially return a sample from comet 1P/Halley during its next apparition within 26 years [5].

Centaurs and Kuiper Belt Objects: Similarly to comets, Centaurs and small Kuiper Belt Objects could inform the primordial composition and early accretion of icy materials in the outer Solar System. Cold Classical Kuiper Belt Objects were deemed to be the most valuable targets, as they have not been affected by planetary migration processes and have remained at their present-day location since their formation. A deep cryogenic sample return from an object like Arrokoth could be feasible in principle.

Challenges, technology needs: Several areas of significant challenges for sample return missions to these destinations have been identified in the first workshop, such as cryogenic sample curation, containment and analysis, in-flight propulsion and its impact on mission duration, preservation of the stratigraphy in core samples, etc. These areas are being further studied, in preparation of the second workshop. At the conference, we will report on both workshops, potential changes since the first workshop, and potential recommendations from the study program regarding future sample return missions and technology development needs.

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