Lunar Sample Return from Multiple Locations is a Critical Capability for Addressing High-Priority Planetary Science Goals

A White Paper submitted to the Planetary Science Decadal Survey 2023-2032

Daniel P. Moriarty III

NASA GSFC / UMCP
daniel.p.moriarty@nasa.gov
301-614-6843

Noah E. Petro

NASA GSFC
noah.e.petro@nasa.gov

Sarah N. Valencia

NASA GSFC / UMCP
sarah.n.valencia@nasa.gov

Stephen Bailey

Deep Space Systems
steve.bailey@deepspacesystems.com

Taylor Morton

Deep Space Systems
tmorton@deepspacesystems.com

Clive R. Neal

Notre Dame
cneal@nd.edu

Signatories: Heather Meyer (JHUAPL), Brett Denevi (JHUAPL), Ryan Watkins (PSI), Samuel Lawrence (NASA JSC), Trevor Graff (NASA JSC), Juliane Gross (Rutgers), Jennifer Whitten (Tulane University), Jessica Flahaut (CNRS/CRPG), Wajiha Iqbal (WWU), Kerri Donaldson Hanna (UCF), Jackie Clark (ASU), Csilla Orgel (ESA-ESTEC), Anal Cassell (NASA ARC), Ross Potter (Brown University), Devanshu Jha (MVJ College of Engineering).

Key Recommendation: Numerous high-priority planetary science goals can be addressed through analysis of diverse lunar samples. In terms of programmatic complexity, effort, and cost, the most efficient approach to collecting these critical samples is a mission architecture capable of returning materials from multiple sites across the lunar surface. Investment in new samples from diverse locations will yield transformative scientific results for decades to come.

1. Introduction

The Moon plays a central role in addressing fundamental planetary science questions relevant to the formation and evolution of the Solar System. Several of these questions *require* sample return from multiple dispersed locations across the lunar surface, as continually emphasized through community documents described in the next section. Historically, robotic lunar sample return missions have been designed to target single locations. While such missions provide important sampling capability, it is not tenable to scale up this approach to sample large numbers of sites due to factors such as programmatic fatigue, funding uncertainties, and overall cost. **Instead, we recommend developing a single-mission architecture capable of accessing multiple surface locations. This enables numerous, diverse science goals to be addressed in a cooperative fashion, rather than pitting researchers against each other in a competitive funding environment.**

We reiterate the need for samples from multiple locations as dictated by high-priority science goals. Here, we discuss two possible architectures for achieving this objective under the scope of a single mission: (1) a refuellable lander and orbital refueling depot enabling multiple trips to the lunar surface, and (2) consolidation of samples on the lunar surface by hoppers/rovers for eventual launch and return to Earth.

2. Science Requirements Dictate the Need for Multi-Site Sample Return

Samples collected by the Apollo and Luna missions shaped our understanding of planetary processes and the history of the Solar System. In 2006, NASA commissioned the National Research Council to prepare for the next phase of lunar science and exploration through an assessment of the highest-priority science objectives. The resulting document, *The Scientific Context for the Exploration of the Moon* (NRC, 2007) succinctly delineates the Moon's unique role in addressing a diverse range of fundamental planetary science questions. In 2017, the Lunar Exploration Analysis Group (LEAG) Advancing Science of the Moon Specific Action Team re-affirmed the relevance of the framework established by the *SCEM* report towards ongoing lunar exploration efforts (LEAG, 2018). The Moon's role as a cornerstone of planetary science (and, specifically, the importance of lunar samples) is continuously updated through the lens of community documents and peer-reviewed publications (e.g., NACSC, 2007; NRC, 2011; Crawford et al., 2012; LEAG, 2016; Shearer et al., 2016; Jolliff et al., 2017; LEAG, 2018; SSERVI, 2018; Jawin et al., 2019; Moriarty et al., 2020a; 2020b; Valencia et al., 2020).

Returning samples from the lunar surface is essential for addressing several of the highest-priority science and exploration goals, as sample return enables detailed chemical and physical analyses possible only in terrestrial laboratories. Typically, each science goal requires sampling specific materials often corresponding to specific areas on the lunar surface. Rock types are variably distributed on the lunar surface, meaning that different science goals dictate the need to collect samples from different areas of the Moon. Furthermore, several science questions related to unraveling geologic history and compositional diversity benefit from analysis of multiple

Figure 1: Diverse lunar samples of critical importance to high-priority planetary science questions are widely distributed on the lunar (a) nearside and (b) farside. To satisfactorily address these science questions, it is essential to develop a mission architecture capable of returning samples from multiple locations. (credit: Clive Neal)

sample types from multiple locations. *Therefore, addressing the full suite of high-priority science goals established by the planetary science community necessitates sampling a diversity of materials from multiple locations on the lunar surface* (Valencia et al., 2020; Moriarty et al., 2020b).

Here, we briefly outline several high-priority science concepts requiring sample return (as first formalized in the *SCEM* report), along with the types and locations of samples required:

- **The bombardment history of the inner Solar System is uniquely revealed on the Moon.** Understanding the flux of impactors through time is critically important for understanding the dynamical evolution of the Solar System, as well as the geological and biological implications of the correlated impact events. Basin formation is an energetic process that melts large volumes of target rock. This process resets isotope ratios in the resulting impact melt, functionally recording the timing of formation. These impact melts can be identified morphologically and compositionally from existing orbital data, and have distinct physical properties facilitating confirmation of sample origin. *Samples of impact melt from multiple lunar basins identified using existing orbital data can reveal the time-dependent impact flux in the inner Solar System.*
- **The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.** The contemporary structure of the lunar crust and mantle is understood to have formed through crystallization of a global, deep melting event known as the “Lunar Magma Ocean.” Magma oceans are thought to be a common feature of large terrestrial bodies, and are therefore a fundamental process driving formation and evolution of rocky planets across our Solar System and beyond. Vast impact structures such as the South Pole – Aitken Basin (SPA) serve as probes to the lunar interior, exposing pyroxene-rich lower crust and upper mantle materials at the surface. Olivine-rich outcrops associated with smaller basins have also been interpreted as exposures of mantle material. Resolving the orbitally-observed compositional differences between probably mantle materials

is a central question in lunar science, resolvable only through sample return. *Regardless, large lunar basin ejecta may represent some of the most accessible mantle materials in the Solar System and provide critical insight into the geochemical evolution of the lunar interior.*

- **Key planetary processes are manifested in the diversity of lunar crustal rocks.** As mentioned above, products of the Lunar Magma Ocean including the primary crust and impact-excavated mantle are accessible at the lunar surface, revealing the Moon's early geochemical evolution. Significant geochemical and geophysical differences are observed between the lunar nearside and farside, necessitating sample return from both hemispheres to understand the mechanisms that formed this dichotomy. The Moon also exhibits a diverse range of secondary crustal products, discussed further below. *Diverse crustal lithologies not present in the current collection are distributed across the lunar surface provide insight into key planetary processes that shaped the Moon, with implications for similar processes on rocky planets across the Solar System and beyond.*
- **The lunar poles are special environments that bear witness to the volatile flux over the latter part of Solar System history.** In particular, permanently-shadowed regions near the poles are among the coldest locations in the Solar System, in many cases exhibiting annual maximum temperatures below 110 K (Prem et al., 2020). These low temperature surfaces trap impinging volatile molecules, eventually forming volatile deposits that are stable over geologic timescales. *Sampling these volatile deposits near the poles will provide a historical record of the lunar volatile cycle, as well as the evolving flux and composition of the solar wind, interstellar volatiles, and volatile-bearing impactors such as asteroids and comets.* These impactors may have also delivered significant quantities of organic materials to the lunar surface. The evolution of these compounds under harsh lunar surface conditions (galactic radiation, impacts, thermal stresses, etc.) has implications for astrobiology. Preserving volatile content in these samples requires special handling capabilities such as vacuum sealing and cryogenic collection and storage.
- **Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.** Across its surface, the Moon exhibits a range of magmatic emplacements reflecting the thermal evolution of the interior. These include widespread mare flood basalts, ancient Mg-suite plutons, volatile-driven pyroclastic deposits, anomalously young irregular mare patches, ring-moat domes, and a series of unusual silicic and other non-basaltic emplacements. Although volcanic materials were collected in the Apollo and Luna missions, they represent only a small sampling of the wide range in age and composition estimated from remote sensing data. Furthermore, the expression of volcanic processes is significantly different on the lunar nearside and farside, requiring sample return from both hemispheres to properly understand these processes. *The age and geochemistry of diverse volcanic materials distributed across the lunar surface reflect the conditions of their formation, providing a benchmark to refine our understanding of volcanism and thermal evolution on the Moon and throughout the Solar System.*
- **The Moon is an accessible laboratory for studying the impact process on planetary scales.** From dust grain accretion to the formation of vast megabasins, impacts are the primary evolutionary driver of the Solar System and its planetary bodies. Large impacts cannot be

Figure 2: The LASSO concept would provide repeated access to the entire lunar surface using a refuellable lander and orbital propellant depot (A). The lander employs an arm-mounted coring drill for sample acquisition (B).

replicated experimentally, and are not well-preserved on Earth. Therefore, we must turn to the extraterrestrial observational record to better understand these fundamental processes. In its rocks, the Moon has preserved a record reflecting impacts over a wide range in scale, from micrometeorite pits to the ~2500 km South Pole – Aitken Basin. *Impact-related materials across the lunar surface record the profound geochemical and thermal effects of impact processes at multiple scales.*

- **The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.** Because the Moon is an airless body that lacks a strong magnetic field, its surface is subject to constant bombardment by micrometeorites, solar wind, and other energetic particles. Additionally, the lack of an atmosphere contributes to an extreme diurnal temperature cycle, subjecting surface materials to thermal fatigue that contributes to regolith development. Understanding regolith formation and weathering processes is key for interpreting remote sensing data, unraveling sample provenance, and developing a sustained presence on the Moon and other planetary bodies. *Lunar regolith samples from across the lunar surface reveal the details of these properties, and may also preserve a record of solar and galactic events through capturing solar wind particles, interstellar dust particles, and recording the galactic cosmic ray flux.*

3. Refuellable Lander / Orbital Refueling Platform

The ability to access materials from widespread locations across the lunar surface would greatly enhance our ability to address numerous high-priority science goals. One approach to achieve this is through multiple spacecraft landings. To date, this would normally require a

sequence of one-off missions, resulting in high costs and burdensome programmatic redundancy. However, *this could be accomplished efficiently through a series of Commercial Lunar Payload Services landers*, as a way to evolve the CLPS program (Voosen, 2018).

Alternatively, *innovations such as reusable, refuellable landers would offer access to samples from multiple locations within the scope of a single mission architecture*, a far more efficient approach. One such concept is currently under development at NASA GSFC. The Lunar All-site Sampler/Orbiter (LASSO) concept advances employs a refuellable lander and an orbital cryogenic refueling depot. *The concept is designed for multiple round trips to unlimited locations on lunar surface, enabling sample collection from a potentially unlimited number of sites.*

The current mission architecture includes a propellant depot in a 1,500-km altitude orbit to reduce propellant boil-off while permitting repeated access to the surface. The fuel stores in this depot would permit ~3 to 4 round trips to any location, including the equator and both poles. The depot/lander tandem are designed to rendezvous with other orbital assets. This permits sample transfer to Earth-bound vehicles. Additionally, the propellant depot is designed to be repeatedly refueled and serviced, thus permitting an unlimited number of trips to the lunar surface (depending only on lander degradation). The current spacecraft design is small and efficient, fitting within the launch constraints of the Falcon Heavy lift vehicle.

As currently designed, the primary sampling mechanism employed by the LASSO lander is a coring drill 10 cm in diameter and 1-2 m in length. While this provides sufficient material to address the relevant science questions, the LASSO lander could be designed to be modular, so that different sampling mechanisms or experiment packages could be outfitted during the normal servicing cadence. This could prove especially useful for sampling volatile-rich materials from polar cold traps, as optional cryogenic sampling techniques could be employed. *The adaptability, flexibility, and utility of such a mission architecture is unprecedented, and represents a significant enabling innovation for achieving numerous high-priority science and exploration goals.*

4. Sample Consolidation on the Lunar Surface

On a smaller scale, hoppers and rovers can also broaden the geographic reach of localized human or robotic sampling campaigns. For instance, there are locations of high scientific interest that are highly challenging for astronauts or large rovers to access. These locations include central peaks of craters, subsurface lava tubes, lunar rilles, and some permanently shadowed regions containing volatiles. Sample acquisition from these areas could be of immense scientific value if there exists the technology to achieve it.

Deep Space Systems (DSS) in Littleton, Colorado has created the concept of ReconDroid - a Reconnaissance Droid for Exploration of Extreme Environments to allow close-up observations and sample acquisition of areas that are inaccessible to humans or conventional surface-based

robotic exploration systems (Figure 3). The ReconDroid is an intentionally simple design with a monopropellant system and autonomous navigation. At 20-35kg, depending on payload and propellant load, the ReconDroid is light enough to easily be carried and setup by a single Crew member or carried and deployed from a small robotic lander or rover. It is refuellable, reusable, and easily repurposed to different mission objectives like sample acquisition. The general design and relative size are illustrated in Figure 4.

With a 1 kg payload of collected samples and a full tank of propellant, the droid can travel a radius of round-trip operations of over 50km. This includes a 10% delta V margin and two 15 sec hover burns, one at the end of each launch for soft landings. This example trajectory and delta V usage are shown in Figures 5 and 6.

The low mass and compact size of the droid allows it to easily be carried by astronauts and stored on rovers. This can extend the two-way range the droid can travel, relative to the deployment zone, up to 150km if it is deployed from a mobile pressurized or unpressurized rover. These increases in range are taken from NASA's established Lunar Excursion Ranges for a single unpressurized rover (10km) and dual pressurized rovers (100km). Figure 7 illustrates these increases in range relative to a reference south pole human landing site (relevant to the upcoming Artemis campaign). The figure also shows how deploying the droid from rovers permits all of Shackleton Crater to be within range, as well as high peaks and permanently shadowed regions with high concentration of volatiles. The droid can hop in and out of these otherwise

inaccessible locations with precision landing, collecting surface samples either autonomously or via telerobotic control. The droid is equipped with lights and high-performance cameras, allowing for photo reconnaissance even in shadowed regions.

In addition to sample return to a human lander base, sample return to Low Lunar Orbit (LLO) can be achieved, which eliminates the requirement of astronaut intervention. The ReconDroid can be outfitted as a small and simple ascent vehicle capable of delivering up to 0.5 kg of lunar samples straight to LLO. The ascent vehicle could be deployed from a robotic lunar lander, collect samples, and then launch itself to LLO where it will rendezvous with a transfer vehicle. This emerging technology could greatly enhance local sample return efforts by allowing for the acquisition of samples typically inaccessible to standard surface operations.

5. Recommendations

As we forge a new era in solar system science and exploration, strengthening our sample return capabilities will be a critical piece of addressing high-priority science goals. These goals dictate the need for samples from widely dispersed locations across the lunar surface. A promising architecture concept to achieve this goal is the use of a refuellable landing vehicle in tandem with an orbital propellant depot. Such a mission would enable multiple trips to the surface, enabling collection of samples spanning a wide range in age, geochemistry, and petrological origin. On a more localized scale, hoppers and rovers can greatly enhance the reach of more typical sampling efforts, enabling access to otherwise challenging areas.

6. References:

- Crawford, I. A., Anand, M., Cockell, C. S., Falcke, H., Green, D. A., Jaumann, R., & Wieczorek, M. A. (2012). Back to the Moon: The scientific rationale for resuming lunar surface exploration. *Planetary and Space Science*.
- Jawin, E. R., Valencia, S. N., Watkins, R. N., Crowell, J. M., Neal, C. R., & Schmidt, G. (2019). Lunar science for landed missions workshop findings report. *Earth and Space Science*, 6(1), 2-40.
- Jolliff, B., Watkins, R., Petro, N., Moriarty, D., Lawrence, S., Head, J., ... & Gaddis, L. (2017). Selecting and certifying a landing site for moonrise in South pole-Aitken basin.
- Lunar Exploration Analysis Group (LEAG) (2016) “*The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities, 2016.*” Roadmap (LEAG 2016).
- Lunar Exploration Analysis Group (LEAG) (2018), “*Advancing Science of the Moon: Report of the Specific Action Team.*” held 7-8 August 2017, Houston, TX.
- Lunar In Situ Resource Utilization (ISRU) (2019), “*Developing a New Space Economy through Lunar Resources and their Utilization.*” Columbia, MD.
- Moriarty, D. P., Neal, C., and Lawrence, S. (2020a), “The Moon is a Special Place.” *Decadal Survey on Planetary Science and Astrobiology 2023 – 2032 White Papers. Bulletin of the American Astronomical Society*.
- Moriarty, D. P., D. P. Moriarty, S. N. Valencia, R. N. Watkins, and N. E. Petro. (2020b). “Illuminating the Lunar Mantle.” *Nature Communications*, (Submitted)
- NASA Advisory Council Science Committee (NACSC) (2007), “*Workshop on Science Associated with the Lunar Exploration Architecture.*” Tempe, AZ.
- NASA (2020), “*NASA’s Plan for Sustained Lunar Exploration and Development.*” Washington, DC.
- National Research Council (NRC) (2007), “*The Scientific Context for Exploration of the Moon.*” Washington, DC.
- National Research Council (NRC) (2011), “*Vision and Voyages for Planetary Science in the Decade 2013-2022*”, National Academies Press, Washington, DC.
- Prem, P. et al., (2020), “Lunar Volatiles and Solar System Science.” *Decadal Survey on Planetary Science and Astrobiology 2023 – 2032 White Papers. Bulletin of the American Astronomical Society*. Washington, DC.
- Solar System Exploration Virtual Institute (SSERVI) (2018), “*Transformative Lunar Science.*” Mountain View, CA.
- Shearer, C. K., Eppler, D., Farrell, W., Gruener, J., Lawrence, S., Pellis, N., ... & Bussey, B. (2016). Results of the Lunar Exploration Analysis Group (LEAG) Gap Review: Specific Action Team (SAT), *Examination of Strategic Knowledge Gaps (SKGs) for Human Exploration of the Moon*.
- Valencia, S. N. et al (2020), “High Priority Returned Lunar Samples” *Decadal Survey on Planetary Science and Astrobiology 2023 – 2032 White Papers. Bulletin of the American Astronomical Society*. Washington, DC.
- Voosen, P. (2018). “NASA to pay private space companies for moon rides.” *Science*, Vol 362, Issue 6417.