

Sample Return from the Earth's Moon

A White Paper for the NRC Planetary Science Decadal Survey, Reflecting the Viewpoints of the NASA Analysis Groups CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials) and LEAG (Lunar Exploration Analysis Group)

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*This white paper has been posted on the CAPTEM website noted above and inputs to it were sought from the planetary science community at large. Numerous comments and suggestions were received from many members of this community, and resulted in substantial revisions and endorsements to this white paper.

Introduction

Samples returned from selected locations on the Moon will provide extraordinary advances in lunar and Solar System science, including (but not limited to):

- Testing the existence of, and duration of, the lunar (inner solar system) impact cataclysm;
- Calibrating crater count chronologies across the inner solar system;
- Testing models of early planetary differentiation, including the effects of giant impacts and magma oceans;
- Determining the moon's lithologic diversity and magmatic processes via analysis of materials of known provenance, including those from deep in the Moon;
- Constraining the Moon's thermal evolution through the range of lunar volcanism (space, time, composition); and
- Developing a better understanding of the formation and modification of impact-basins.

In general, analyses of returned samples offer nearly unlimited opportunities – samples can be subjected to any analytical procedure possible in any laboratory on Earth (constrained only by sample mass). Analyses of returned sample are not limited in quality or number of analyses, flexibility and scope of investigations, use of new techniques, or responses to new scientific questions. Although lunar meteorites are analyzed in this fashion, their value is limited by lack of geologic context – we do not know specifically where they came from. Analyses of returned samples complement orbital and *in-situ* spacecraft investigations, providing ground truth for their spectral and geophysical measurements.

This white-paper answers three questions about sample return from the Moon:

1. Why is sample science crucial to understanding the inner planets?
2. Why are analyses of returned samples preferable to *in situ* analyses?
3. Why is it important to return more lunar samples to Earth?

The Importance of Sample Science

The importance of sample science, particularly for the Moon, is amply demonstrated by past experience, and is called for specifically in high-level planning documents for lunar science and exploration (e.g., NRC, 2003, 2007; LEAG, 2009). Analyses of samples (*in situ* or in laboratory) provide crucial data that cannot be obtained by remote sensing, and act as its ground truth. Current and recent lunar orbiters carry instruments that explore the lunar surface in unprecedented detail for morphology, mineralogy (by IR spectrometry), and bulk chemistry (e.g, by X-ray, gamma-ray, and neutron spectrometry). However, orbital investigations are limited in their spatial resolution (e.g., hundreds of kilometers for neutron methods) and in depth resolution. Sample analyses can provide complementary data at smaller scales – meters to nanometers – defining the actual chemical and physical properties that are sensed remotely. For instance, remote sensing has long shown that older lunar surfaces are redder, but it took transmission electron microscopy of samples to show that the redness is caused by nanophase grains of iron metal in agglutinates and coatings.

In addition, there are many crucial scientific investigations that cannot be done remotely, and require close contact with samples. Many are described below, and include: imagery of textures, structures, and microstructures, detailed minor/trace mineralogy, precise chemical compositions (major, minor, and trace elements), stable isotope ratios, and radiogenic isotope ratios and age dating.

The Value of Returned Samples versus *In Situ* Analyses

The inherent restrictions and limitations of spacecraft mean that *in situ* analyses of samples will almost always be inferior to those obtainable on the Earth. Spacecraft analyses will lack state-of-the-art accuracy and precision, and may be limited by our preconceptions about what we expect to find. In contrast, studies in Earth laboratories can be of the highest quality possible, and can be tailored to fit the samples exactly. In addition, studies of returned samples will take advantage of all the instrumentation and capabilities available on Earth, not only at the time of the return but far into the future, thus benefiting from technological advances in analytical equipment. Therefore, analyzing extraterrestrial samples on Earth affords infinite flexibility to respond to what is actually in the sample. We only need to collect samples on the Moon, and transfer them to the Earth.

Quality

The analytical precision and accuracy obtainable in modern Earth-based laboratories exceeds that of the best spacecraft instruments, because of the unlimited availability of: resources, environmental controls, operator intervention, and sample preparation. Earth-based instruments can be designed for nearly unlimited resources, while spacecraft instruments are severely restricted by available energy, volume, time, CPU power, memory, data rate, etc. Earth-based instruments can be delicate and may be housed in benign environments (e.g., fixed temperature, low vibration, free of magnetic fields), while spacecraft instruments must survive shocks, temperature extremes, vacuum, hard radiation, etc. Earth-based instruments can be optimized, tended, and fixed in real time by skilled technicians, while spacecraft instruments must work ‘as is’ without repairs. Finally, Earth-based instruments can be designed for specialized samples (e.g., polished thin sections or thinned TEM mounts) prepared in complex laboratories, while spacecraft instruments must include sample preparation or do without. With these advantages, it is no surprise that Earth-based instruments out-perform the best spacecraft instruments (e.g., McSween et al. 2006).

The progress of instrument development also favors Earth-based analyses of returned samples over spacecraft analyses. Spacecraft require significant time to design and construct, and subsystem (e.g., instrument) designs can be frozen several years before nominal launch. If launch is delayed (e.g., MSL), flight instrument designs can be 5-10 years out of date on arrival at their destination. On the other hand, Earth-based instrumentation will continue to improve, and one can reasonably expect better analyses on sample return than had been available on spacecraft launch (e.g., SIMS analyses on Genesis samples, and SIMS analyses for H in lunar glasses; Saal et al. 2008).

Scope and Flexibility

Earth-based analyses of returned samples are essentially unlimited in scope and flexibility – with all Earth laboratory instruments available, one can analyze a returned sample for any sort of structural features, element abundance, isotope ratio, or complex compound. Further, that feature or abundance or ratio can be re-analyzed to better precision, if needed. On the other hand, spacecraft investigations are necessarily limited in scope and flexibility. A spacecraft has limited and invariant instrumentation, which cannot be augmented in flight, nor altered in response to unexpected findings.

Future Investigations

A returned planetary sample is a gift that keeps on giving. It can be studied for generations to come, analyzed and re-analyzed as methods improve and as new scientific questions arise.

The importance of returned lunar samples is illustrated by the changing ideas of the Moon's origin and early history. The Apollo samples overturned the idea, prevalent in the 1960s, that the Moon was an undifferentiated body; instead, the Moon was proved to be strongly differentiated, and to have had a magma ocean. Emphasis soon shifted to the origin of the magma ocean in the context of the Earth-Moon system, and now favors the giant impact model for the Moon's origin. Isotopic analyses of returned samples now provide crucial constraints on the nature of the giant impactor and on chemical and physical conditions following the impact (Humayan and Clayton, 1995; Spicuzza et al., 2007; Pahlevan and Stevenson, 2007).

An excellent example of improved techniques is in radiogenic isotope dating – the Apollo samples are now being analyzed with techniques unimagined at samples return. These include at least five radiochemical tracer and age-dating methods: ^{187}Re - ^{187}Os , ^{190}Pt - ^{186}Os , ^{176}Lu - ^{176}Hf , ^{146}Sm - ^{142}Nd , ^{182}Hf - ^{182}W . From them, we have refined the age of the Moon, learned more of when and how its crust formed, learned more of how it is related to the Earth, and learned how quickly planets (and the Moon) formed early in the solar system. If the Apollo missions had not returned samples, none of these results would have been possible.

The Need for New Lunar Sample Returns

Answers to many crucial questions of lunar science and exploration will require new returned samples, in addition to those from the Apollo and Luna missions, and the lunar meteorites recovered on the Earth (Jolliff et al., 2006; Shearer et al., 2006, 2007; Neal 2009). The available returned samples are from a small area of the lunar surface, and were selected for the simplest science goals within severe operational constraints. Answering most current questions of lunar science will require analyses of samples from specific locations (mostly distant from the Apollo-Luna region; e.g., non-equatorial, far side), informed by remote sensing and subjected to the full suite of mineralogical, lithologic, geochemical, and geochronological analyses.

Since the Apollo and Luna missions, new samples from the Moon have been recognized among the meteorites, both from Antarctica and from hot deserts. Lunar meteorites are, in effect, sample returns without the crucial contextual data of place of origin. The lunar meteorites are samples from random sites, and so provide (rough) global coverage and averages, and sampling of sites not visited by Apollo or Luna. Among the meteorite launch sites are several with lithologies not seen in returned samples, several likely from the farside (not visited by Apollo or Luna), and likely some from special places recognized by remote sensing, e.g. the meteorite Dhofar 961 may be from the South Pole / Aitken basin (Jolliff et al., 2009). On the other hand, most science questions cannot be addressed with lunar meteorites because we don't know exactly where they are from.

Below are some top-level science investigations that can be advanced through analyses of returned lunar samples (see Ryder et al. 1989; Jolliff et al. 2006; Shearer, 2006; Shearer et al. 2007; NRC 2007; Neal 2009).

(1) Impact History of the Inner Solar System: The Moon is the most accessible target to understand impact rates, timing, and processes in the inner solar system, including the Earth, Mercury, and Mars. This early impact environment was a primary force in shaping the early Earth, including its composition, the evolution of its atmosphere, and early tectonics, and the origin and evolution of life. Further, large impacts may have had a substantial effect on planetary-scale asymmetry on both the Moon and Mars.

Understanding the impact history of the Moon, and thus the inner solar system, requires precise radiometric ages for samples along with corroborating information such as trace elemental composition and geologic context (e.g., the impact melt of a specific crater or basin). Investigations possible with these sorts of data include:

- Refining the age calibration of crater-count chronology in the solar system, and thereby the flux of impactors as a function of time. Returned lunar samples are our only absolute calibrations of crater count ages. However, the calibration remains imprecise, especially for young ages (e.g., lava flows; Hiesinger et al. 2003), which propagates to enormous uncertainties in crater count ages for other planets (like Mars).
- Testing the existence of a ‘lunar cataclysmic bombardment’ at ~3.9 Ga. Evidence suggests that the inner solar system experienced a spike in impact rates at about this time, with enormous implications for solar system dynamics, astrobiology, etc. To determine if this lunar cataclysm was real, one needs precise ages of the lunar basins (better than ± 0.02 Ga, by multiple methods, emphasizing the oldest and youngest basins (South Pole - Aitkin & Orientale). This level of precision is achievable only in terrestrial laboratories.

(2) Early Planetary Differentiation & Internal Structure: The Moon presents a good opportunity to characterize the early physical and chemical differentiation of a major planetary body; the Earth’s original differentiation has been obscured by its vigorous mantle convection and plate tectonics. The Moon differentiated early and rapidly via a ‘magma ocean,’ which produced the Moon’s ferroan anorthosite crust and left chemical traces in its later magmas. Indeed, the magma ocean concept arose only through analyses of returned samples (Wood et al. 1970). Understanding the formation and evolution of the magma ocean and its products requires precise analyses of trace elements abundances (e.g., rare earth elements) and radioisotope ratios in selected lunar rocks and minerals, i.e., on returned samples. The magma ocean concept has been applied (though not without controversy) to the early histories of the Earth, Mars, and differentiated asteroids like 4 Vesta. Although the idea of a lunar ‘magma ocean’ is nearly 40 years old, many questions remain, including:

- What were the lateral and vertical extent of melting, i.e., was the Moon completely molten? If not, did any unmelted “primitive” mantle participate in later dynamic or magmatic events?
- If other planetary bodies had magma oceans early in their histories, how do the properties and products of magma oceans vary with planetary size and composition?
- What are the compositions and mineralogies of the Moon’s lower crust and upper mantle? A Decadal white paper from Petro et al. advocate return of such material from the South Pole – Aitkin basin?
- Is the Moon’s crustal asymmetry related to the formation or crystallization of the magma ocean? How did the lunar crust change through time both on the near and far sides?

(3) The thermal and magmatic history of the Moon: The Moon preserves a record of thermal

and igneous evolution following its magma ocean, with basalt eruptions extending from 4.35 to ~1 Ga (e.g., Nyquist and Shih, 1992; Hiesinger et al. 2003; Terada et al, 2007). These eruptions, coupled with geophysical constraints, can provide trace element chemical and isotopic data that would strongly constrain the Moon's mantle dynamics, and thereby those of other terrestrial planets. Among the science questions of the Moon's thermal and magmatic evolution are:

- How did the spatial distributions, compositions, and rates of lunar magmatism change over time? What do those changes imply about changing mantle dynamics and compositions?
- Why are mare basalts more abundant on the lunar nearside? Is this asymmetry related to crustal thickness after early differentiation, to mantle structures, or to impact events?

(4) Evolution of the lunar regolith: The lunar regolith, the fragmented 'soil' at the lunar surface, hold records of the Moon's interaction with the space environment, hosts pieces of lunar and impactor rock types, dominates the Moon's response to remote sensing probes, and is an analog for regolith formation on other airless planetary bodies. Although studied extensively, many questions about the regolith remain, requiring in-depth analyses of returned samples, e.g.:

- What are the sources, histories, and intensities of the flux energetic charged particles (solar and cosmic) impinging on the lunar surface?
- By which mechanism do lunar processes (e.g., solar wind interaction, impact gardening, micrometeorite volatilization and mass redistribution) affect the remote sensing response of the regolith, and how can one invert remotely sensed data to recover original compositions, original mineralogies, and extents of processing?
- What are the sources and abundances of extralunar materials in regolith, and their variations over time? Lunar regolith contains elemental clues about the material that impacts it, and rare asteroidal materials have been recognized in lunar regolith (e.g., Zolensky 1997). Similarly, it has been proposed that lunar regolith may preserve early materials from other planets, including Earth (Armstrong 2002; discussed in a Decadal White paper by Fries et al.).

(5) Volatile reservoirs on airless planetary bodies: The Moon is markedly depleted in volatile constituents (e.g., H, water, Na, K) compared to the Earth. Yet, recent neutron spectrometry indicates that hydrogen is concentrated significantly in regolith near the lunar poles, probably in permanently shadowed regions. The nature(s) and source(s) of these H enrichments are not known – water ice, adsorbed gas, or implanted ions, sourced from comets, primitive meteoritic material, solar wind, or indigenous lunar outgassing. More recently, some volcanic glasses (returned by Apollo missions) have been found to contain significant water, perhaps tenths of a percent H₂O by weight on eruption (Saal et al. 2008). Thus, the distribution of lunar volatiles has become a wide-open question, answerable partly by remote sensing studies (e.g., bistatic radar) but most definitively by sample studies (notably of stable isotope compositions) in advanced laboratories on Earth. Among other related questions related to volatiles, one can cite:

- What volatile components drove the lunar pyroclastic eruptions, and did the volatiles differ among different eruptions? What are the indigenous lunar (mantle) reservoirs of volatiles?
- How important are exogenous volatile inputs to the lunar surface, both for water and for organic matter? Are those exogenous inputs relevant for pre-biotic chemistry?

(6) Feed-outward & -forward: Lunar samples will not be the only ones returned to the Earth – returns are planned for samples from Mars, asteroids, and comets. The Moon’s proximity to the Earth allows lunar sample return to act as a testbed for robotic technologies enabling sample return from more distant planetary bodies. The varied lunar environments permit this technology development to be aligned with sample type rather than a planetary body. For example, technology to gather 1 cm rocks using an automated sampling rake would be valuable on the Moon, but also Mercury, Phobos, Deimos, asteroids, etc. Similarly, technology developed to return ice from lunar cold traps would feed forward to ice returns from comets and Mars.

Summary

Sample return is a long-term investment in knowledge, augmenting and informing our understanding of nearly all aspects of lunar science, including surface processes, thermal and dynamic histories, internal structure, volcanic processes, impact history, and astrobiology. Returned lunar samples are, and will be, inheritances that will serve lunar and planetary science for generations. *In situ* analyses are, of course, critical to exploration of the solar system, but cannot address all of NASA's goals and visions. Only through careful study of returned samples can we realize the full potential of the instrumentation and analytical skills that are available here on Earth.

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