Investigating Impact Processes at all Scales: The Moon as a Laboratory

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Executive summary

Due to its location, history, and preservation, the Moon is an ideal laboratory to study impact cratering – a fundamental geological process – at all scales. Additionally, impact cratering studies have important crossfield applications covering planetary formation, structure, and evolution. Outstanding impact questions include how impacts deliver, distribute, and remove volatiles from the poles; how rock breakdown affects regolith formation; and how cold spots and impact basins form. To address these questions, we recommend in situ lunar studies (sampling and geophysical methods) with the support of orbital observations and theoretical and experimental studies. Recommended sampling sites include the polar regions and the South Pole-Aitken basin. The Moon has been previously highlighted as an important laboratory for impact science. This paper reinforces its importance for the coming decade.

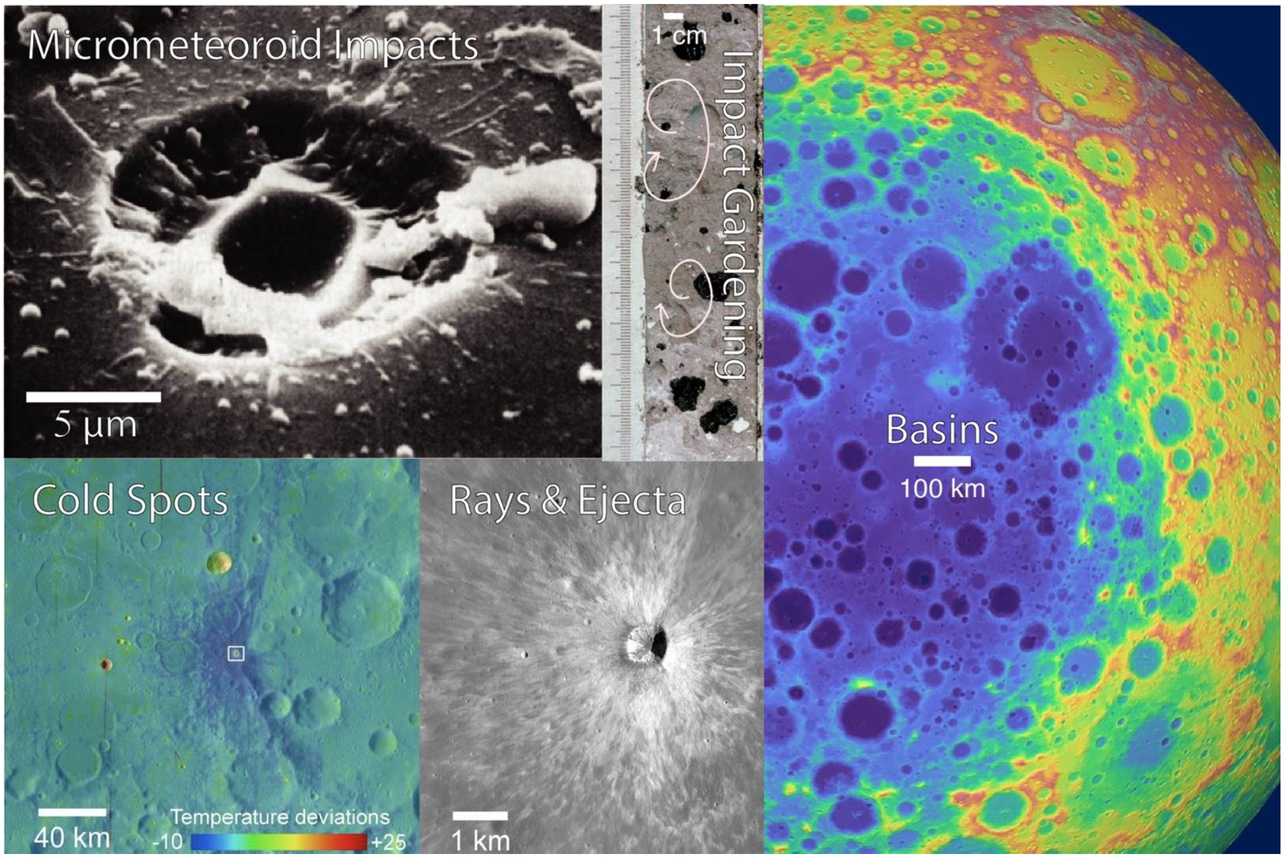

Figure 1: Impacts at all scales on the Moon. Clockwise from the left: Image of a micron-scale **micrometeoroid** impact crater [10]. Evidence of **impact gardening** in the Apollo 16 core 60009 showing a depth-distribution of dark space weathered material. South-Pole Aitken **Basin** (image credit: NASA / GSFC / University of Arizona). A **cold spot** and bright **rayed ejecta** surround a 1 km crater [24].

1. Introduction

Impact cratering is a fundamental geological process acting over a considerable range of size scales (sub-mm to super-Mm) which affects all bodies in the solar system; it is, therefore, a vital process to understand. **Impact cratering is, additionally, an important crossfield science that supports studies of planetary formation, structure, evolution, and human exploration of the solar system** through processes such as volatile delivery, melt differentiation, and climate change. For decades analytical, laboratory, experimental, numerical, and remote and field study investigations have taken place to better understand all aspects of the impact cratering phenomenon.

Investigation of impact craters on Earth is limited due to active surface processes: many larger 'complex' craters are buried (e.g. Chicxulub, Mexico) or highly eroded (e.g. Sudbury, Canada) and only a few relatively small 'simple' bowl-shaped craters are well preserved (Meteor Crater, Arizona). Earth's atmosphere protects the surface from the continuous rain of small meteorites, which fundamentally shape the surfaces of airless bodies across the solar system. Consequently, as many terrestrial impact craters are erased or prevented from forming due to atmospheric disruption of incoming objects, studies of impact craters (and their physical and chemical effects) on other planetary bodies are required.

Compared to Earth's neighboring planets, moons, and asteroids, the Moon is an ideal location to study impact processes because: 1) its surface acts as a record of 4+ billion years of impact history, 2) craters at all scales (sub-mm to super-Mm) are extremely well-preserved, 3) it is relatively accessible for remote and *in situ* studies, and 4) has a rich legacy of scientific investigation, *in situ* exploration, and sample return. The Moon has previously been identified as an ideal laboratory for studies of impact processes by the "Scientific Context for the Exploration of the Moon" (NRC 2007) [1] and by the LEAG (2016) exploration roadmap [2].

We advocate the Moon as an ideal body to study impact processes at all scales. Here, we outline key outstanding impact science questions that can be addressed through theoretical, experimental, remote, and *in situ* studies on the Moon in the next decade. What we discover from, and on, the Moon will have relevance across the solar system.

2. Small scale processes

2.1 Continuous Impact Processes: Micrometeorites and Secondary Impacts

Understanding the physics and distribution of micrometeorite and secondary impacts is critical for the correct interpretation of surface observations from remote sensing, *in situ* studies, and human exploration. The continuous rain of small impactors onto airless planetary surfaces, including Earth's Moon, control physical and chemical alteration (space weathering); surface stratigraphy; and the delivery, preservation, and accessibility of water ice. For bodies like the Moon, the smallest impacts mechanically redistribute surface material [e.g. 3-6]. At smaller asteroids and comets, the collisional products themselves feed the zodiacal dust distribution. Mutual collisions between meteoroids in the zodiacal dust cloud also serve to redistribute zodiacal mass into smaller fragments, which are eventually shed from the solar system [7]. While many processes are governed by micrometeorite impacts, it is difficult to constrain the physics of these small impacts, as reproducing solar system impact conditions of 10s km/s impact speeds with micron to millimeter-sized impactors is difficult in a laboratory setting. Fortunately, the Moon's impact environment provides an excellent laboratory to study these processes in detail. Through improved models and experiments validated by observations of how these processes have altered the surface of the Moon, we can characterize the physics of hypervelocity micrometeoroid impacts and answer these open questions: **How does energy partition for impacts into fluffy regolith surfaces? How does collisional fragmentation vary as a function of impactor size and speed?**

These small impacts pose a hazard to the people and tools we send to the Moon. Understanding the frequency and energy of these small impacts will be critically important for future human endeavor on the Moon and beyond.

Secondary impacts, like micrometeoroid impacts, have recently been shown to be an important impact process over geologic timescales [5, 7]. Impact gardening is the process by which impacts mechanically churn regolith material, removing grains from depth and re-depositing them near the surface, and is dominated by secondary impacts. Explorations of the impact-driven evolution of lunar regolith provide insight into the depth profiles of cosmic ray tracks, volatile elements, abundance of cosmogenic radionuclides, percentages of different lithologic components, and grain size distributions [e.g. 9-13]. Each study contributes to our understanding of the process and consequences of impact gardening and its wider influence on lunar stratigraphy; the lifetime of rays and other surface features such as density and albedo anomalies; and the burial, exposure, and breakdown of volatiles and rocks. In the decade 2013-2022, studies have shown that understanding the rate and extent of gardening also informs the depth to, and preservation of, water ice in the lunar polar regions [e.g. 14].

Impact processes are one of the few devolatilizing phenomena that polar regions, and notably permanently shadowed regions (PSRs), are vulnerable to. If we wish to utilize water on the Moon as a human exploration resource, we must understand how continuous impact processes deliver, redistribute, and remove it. While surfaces near the lunar poles are exposed to appreciable fluxes from high-inclination meteoroids [6], equatorial observations of lunar exospheric water indicate the Moon is currently losing water through meteoroid bombardment [15, 16]. Water ice has been confirmed to exist on, and mixed within, the regolith of the lunar polar regions [e.g. 17,18]; however, *in situ* evidence is lacking. A polar orbiting spacecraft equipped with a dust analyzer and neutral mass spectrometer could measure appreciable quantities of lunar ejecta near the poles to constrain the evolution of volatiles in the polar region [6]. Through models and experiments, we should seek to answer the following critical science questions: **What is the total flux of impactors to the lunar polar regions and how does it weather and redistribute polar material? How efficient are micrometeoroids at liberating water from the polar regions? Is impact gardening a destructive or protective force for volatiles in permanent shadow?**

Beyond the Moon and its poles, micrometeorites and impact gardening through secondary impacts contribute to the surface space weathering throughout the solar system. “Understanding space weathering effects is critical to the correct interpretation of surface observations from remote sensing and *in situ* studies” (NRC 2011 [19], p. 199). The anhydrous silicate bodies of the inner solar system weather differently from the volatile-rich bodies and those composed of abundant hydrous minerals (C-complex asteroids, and outer solar system satellites); the micrometeorite impact products of both are poorly understood. Studying the physics and chemistry of space weathering effects in different environments are areas of active research [e.g. 20-22] and the Moon is a keystone for this. Experimental and theoretical studies of micrometeorite impact products on the Moon can help us to understand the following science questions: **What is the mechanism that forms the microphase iron in agglutinates (Oswalt ripening, formation in melt versus vapor, H-enriched melt)? How important is the role of pre-implanted solar wind in order to form nanophase iron? How are the characteristics of these *in situ* maturation processes expressed in remote sensing data** [i.e. 23, 24]**?**

2.2 Cold Spots

Cold spots have recently emerged as a new class of lunar impact phenomena. Anomalously cold nighttime surfaces, first identified from aboard the Apollo 17 Command-Service Module [25, 26], have recently (through LRO Diviner data) revealed the ubiquity of these thermally distinct surfaces and their association with apparently young craters [27]. These craters, with rocky interiors and ejecta that remain warmer at night, are surrounded by extensive regions ~10 – 100 crater radii that remain colder than the surroundings. The size-frequency distribution of cold spot source craters constrains the lifetime of cold spots to no more than ~1 Myr; they are apparent around only the youngest craters, including several of the largest craters observed to form during the LRO mission [28]. The persistence of the colder temperatures throughout the night indicates the regolith of cold spots has a lower thermal inertia that extends to a depth comparable to the diurnal thermal wave penetration depth (several tens cm). This volume of material far exceeds that of the excavated crater by orders of magnitude, ruling out a layer of deposited material as a source for the cold spot. The physical process that modifies the regolith to produce cold spots remains unknown. The ubiquity and ephemeral nature of the cold spots suggest the process of cold spot formation plays a fundamental role in the regolith structure and possible overturn as every square meter of regolith must have been a cold spot at some point.

Orbital observations have played a critical role in the discovery and initial characterization of cold spots; however, ***in situ*** **observation of their fine-scale surface structure and density structure at depth, enhanced with laboratory experiments and computer simulations, will be needed to constrain the formation process.**

2.3 Rocky Craters

Impactors at all scales spend some of their kinetic energy fracturing and fragmenting target materials. Large impactors—those that produce km-sized and larger craters—eject fragments of intact or brecciated rock onto the lunar surface, where they subsequently experience ongoing impacts from smaller bolides, including micrometeorites. Lunar craters, unlike terrestrial ones, often preserve their ejecta deposits. Because of the power-law size distribution of impactors arriving from their Earth-crossing orbits, newly ejected boulder-sized fragments are subjected to a nearly constant rain of micrometeorites and occasional disruption by larger projectiles. The cumulative effect, over time, is the breaking of boulder-sized fragments into smaller pieces by a combination of “sandblasting” and catastrophic rupture [e.g. 29]. As fragments become smaller, they can also be covered by regolith churned up by nearby small impacts in the continuous “regolith gardening” process [e.g. 5, 30]. By measuring boulder abundance in the parent crater ejecta, parent crater ages can be estimated. In the past decade, thermal infrared data from the LRO Diviner instrument have provided a means of quantifying the surface density of exposed rocky fragments larger than ~1 meter in size [e.g. 27]. These measurements, combined with absolute model ages for several “calibration craters,” including Copernicus and Tycho, lead to an empirical relationship between the rockiness of craters’ ejecta and their age [31]. This result has been used to examine impactor flux over the past billion years. This analysis showed strong evidence for a 2-3 factor increase in the impact flux at both the Earth and the Moon near 270 Ma [32]. This illustrates the potential for observations of rocky craters to address fundamental questions of lunar chronology.

Understanding rock breakdown processes is key for understanding regolith formation on airless bodies; yet even for the Moon, fundamental questions about rock degradation and regolith formation remain. These include: the interplay between size-dependent variations in impactor flux and the protective effect of pre-existing regolith; the relative importance of impact-induced versus thermally-induced fragmentation; and the relative rates of fragmentation versus covering by regolith. **New information is required to address these issues, including accurate absolute ages for large young craters, either from returned samples with full knowledge of their**

provenance and association with the target craters, *in situ* dating, or both (see whitepaper by Ghent et al. titled "Assessing the Recent Impact Flux in the Inner Solar System: 1 Ga to Present").

2.4 Crater Rays

One of the most striking features of relatively "recent" lunar impact craters are their rays - highly pulverized, optically bright material that can be ejected distances tens of times a crater's diameter. Rays can be placed into three classes explaining why their albedo differs from their surroundings: compositional differences, maturity differences, and a combination of these [33]. The mechanism and source of the ejecta responsible for rays remains poorly understood, though investigations using ever-evolving computational models have shown various mechanisms for ray creation that require roughness on the projectile and/or target [34].

Due partly to a lack of suitable data and means to study them, many issues regarding crater rays remain poorly understood, including: how long it takes a specific region of the lunar surface to optically mature to saturation; how long rays persist and details of their evolution; the characteristic roughness of the Moon at all scales that may influence cratering processes; and possible hazards that ray formation might present to lunar exploration. Further work requires continued, detailed study of the nature of the upper lunar regolith, including grain size, porosity, fracturing, evolution, maturation, gardening, layering, and mixing. This must include laboratory experiments as well as remote sensing; *in situ* lunar surface samples would be ideal, along with the production of accurate and inexpensive lunar soil simulants. Regular advances are being made in computing power and computational models; it is expected that **refining models of crater excavation and ejecta emplacement will significantly improve understanding of the formation and nature of crater rays.**

3. Large scale processes

3.1 Impact basins

At a rim diameter of ~200 km on the Moon impact basins are formed, defined as having two ("peak-ring basins") or more ("multi-ring basins") concentric topographic rings. Based on improved image, topography, and gravity data in the past decade [35, 36], 16 peak-ring basins and 11 multi-ring basins have been identified. The prevailing dynamic collapse model for the formation of topographic interior peak-rings based on numerical models [e.g. 37] includes the collapsing of deeply sourced, over-heightened central-peak material that is subsequently thrust over the inward-collapsed basin walls to form the peak ring, in agreement with drill cores retrieved from the peak ring of the terrestrial Chicxulub basin [38]. However, despite numerous numerical and experimental studies [e.g. 39, 40], the exact formation of the larger multi-ring basins remains unclear. Additionally, the occurrence of transitional central structures on the Moon (e.g. Antoniadi) are not well understood [41]. These can be elucidated by more detailed remote sensing and *in situ* analyses combined with refined numerical models.

Numerical models constrain the depth-of-origin for peak-rings and excavated material to be ~0.1-0.2 times the basin diameter, in agreement with Chicxulub peak ring drill cores [38]. Peak rings on the Moon should, therefore, contain lower crustal material [37, 41]; larger multi-ring basins, such as Orientale or South Pole-Aitken (SPA), could have even excavated mantle material [40]. Gravity data can be used to constrain the composition of central peaks and ring massifs [42] and thereby further constrain excavation depths. ***In situ* analyses and sampling at peak-ring and multi-ring basins would offer otherwise inaccessible lower crust or even**

upper mantle lithologies. Samples of such material, if present, would allow insights not only into the formation of basins but also into the structure and evolution of the Moon. Determining the composition of the lower crust and bulk Moon is a key NRC [1] goal (3c). The largest lunar basin, SPA, which likely excavated mantle material, has already been identified as a priority target for sample return [2, 19], and is still strongly advocated (Jolliff et al. "Sample Return from the Moon's South Pole-Aitken Basin" white paper). Studies at Schrödinger basin, located within SPA, would be able to address the majority of the NRC [1] goals [46] and help verify ring-formation at basins of all scales. **Determining the structure of multi-ring impact basins is a key NRC [1] goal (6a).**

3.2 Melt sheet differentiation

Due to the pressures involved (10s-100s GPa), large-scale impacts will melt a significant volume of target rock. Chemical differentiation is thought to separate these melt sheets into varying lithologies; evidence of this has been seen in terrestrial craters (e.g. Sudbury and Manicouagan, Canada). Melt differentiation in some of the largest lunar basins (such as SPA and Orientale) has recently been evaluated through melt modeling and analysis of remote sensing datasets [43, 44, 45]. This is particularly important as these **large impacts are likely to have melted significant volumes of lower crustal and mantle material** [e.g. 40] **providing key information on lunar composition**. Additionally, **samples of these melt sheets would provide definitive basin ages** (samples from SPA, Nectaris, and Orientale would help constrain the timing of the basin-forming epoch (NRC [1, 19]). **The age of SPA is particularly pertinent, as it ranks among the highest priorities in lunar science** (NRC [2, 19]) and given opposing views on whether SPA formed before [43] or after [45] a mantle-overturn event. Samples would, therefore, provide information into the relative timing of these two significant events (suggested locations for SPA include the central peak of Antoniadi, as well as the walls of Schrödinger basin [43]). *In situ* geophysical methods such as seismic surveys (NRC [19], Neal et al. "The Scientific Rationale for Deployment of a Long-Lived Geophysical Network on the Moon" white paper) and electromagnetic methods (e.g. DC resistivity) could also be used to infer density and structural changes in the subsurface, further elucidating the nature of melt sheets. **Characterizing the existence and extent of melt sheet differentiation is a key NRC [1] goal (6a).**

4. Recommendations

Here, we have advocated the Moon as an ideal laboratory to study impact cratering processes at all scales. To address many of the important, outstanding questions highlighted, **we primarily recommend *in situ* studies and continued support of models and remote observation of impact processes on the Moon.** Through sampling (with laboratory analysis) and geophysical methods, this approach would provide:

- Access to important lithologies (e.g. regolith, lower crust, upper mantle).
- Absolute radiometric crater dating (young and old).
- Formation process constraints for impact basins, cold spots, and crater rays.

Recommended sampling sites include:

- Polar region craters (e.g. within South Pole-Aitken basin) for constraining the basin-forming epoch, investigation melt differentiation, and volatiles.
- Young craters for cold spots.
- Copernicus or Tycho for crater rays.

We also recommend new and continued orbital observations and theoretical investigation of impact processes at all scales. Work over the last decade has shown that **understanding the physics and distribution of micrometeorite and secondary impacts is critical for the correct interpretation of surface observations from remote sensing, *in situ* studies, and human exploration.** Due to the crossfield nature of impact cratering, such studies would also support planetary formation, structure, and evolution work. Results will be relevant to bodies throughout the solar system.

The importance of the Moon for impact cratering science is well demonstrated [1, 2, 19]. It will remain a vital laboratory for impact cratering processes in the coming decade.

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