

Recent Advancements in Lunar Science and the Future Exploration of the Moon

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Abstract

This contribution reviews some of the recent advancements in the field of lunar science based upon remote sensing results from a number of spacecraft missions to the Moon and laboratory-based analysis of lunar samples. Perhaps, one of the most exciting recent discoveries in lunar science has been the detection of water on the lunar surface and in the lunar samples. These new findings have significantly improved our understanding of the evolution of the Moon and are helping redefine our objectives for the future exploration of the Moon.

1. Introduction

The first decade of the 21st century witnessed a renewed interest in lunar exploration by the global community with an armada of spacecraft missions launched to study the Moon from orbit (e.g., European Space Agency's SMART-1, India's Chandrayaan-1, China's Chang'e-1, Japan's Kaguya and NASA's LRO). Chandrayaan-1 and LRO also carried additional probes (Moon Impact Probe (MIP) and Lunar CRater Observation and Sensing Satellite (LCROSS)), which were specially designed to detect water and other volatile species in the lunar regolith through impacts into regions of the Moon which were suspected to contain significant deposits of water/ice. In addition, a number of sophisticated instruments onboard these recent spacecraft were utilized for remote sensing studies of the lunar surface both at a global scale as well as at local scale resulting in some spectacular new findings [e.g., 1, 2]. Whilst these spacecraft observations were ongoing, scientists were busy analysing Apollo rocks and lunar meteorites, yielding equally exciting results [e.g. 3-5].

2. Lunar volatiles

Infrared spectroscopic measurements of the lunar surface from three spacecraft have unambiguously detected absorptions near 3 μ m on the lunar surface (top few mm) that are almost certainly an evidence for the presence of hydroxyl (OH) or water [1,6,7]. All three experiments also show that the water related absorption increases toward the lunar poles.

These reports of water on the lunar surface coincide with intense interest in water at lunar poles. The permanently shadowed craters near the lunar poles are thought to provide perfect traps for volatile material migrating near the polar regions. NASA's LCROSS mission targeted one such polar region by crashing a large spacecraft into a polar cold trap. Initial results seem to confirm not only the presence of water/ice in this region of the Moon but also several hydrocarbon compounds [http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.html]. The MIP instrument onboard Chandrayaan-1 also detected water in its vapour phase in the tenuous lunar environment through *in-situ* measurements carried out by CHANDRA Altitudinal Composition Explorer (CHACE) payload. CHACE detected a trend of increasing concentration of H₂O pole ward (maximum at ~60-70° S) which is ascribed to temperature variation and consequent changes in the sublimation rate with respect to latitude and the availability of water ice [8].

Since early 1970's, based upon laboratory investigations of lunar samples returned by the Apollo missions, the consensus among the lunar science community has been that the lunar rocks are entirely dry, and by extension, the Moon is always thought to be completely dry. A paradigm shift in this thinking occurred when Saal et al [3] reported detection and quantification of water and other

volatiles (e.g., Cl, F, S) in lunar volcanic glasses. Around the same time, other workers were using stoichiometry to estimate water contents in apatite from lunar samples to argue a case for a wet lunar interior [e.g., 9]. Most recently, direct measurement of water and its Deuterium/Hydrogen (D/H) isotopic ratio in lunar apatites have been reported, confirming the presence of water in lunar magmas and providing hints at possible sources of lunar water [e.g. 5, 10,11].

3. New constraints on timing and duration of mare volcanism

Constraining the timing and duration of mare volcanism is crucial for our understanding of the thermal evolution of the lunar interior through time. Remote sensing studies of the Moon have indicated existence of mare regions as old as 4 Ga and as young as 1 Ga [12, 13]. In contrast, most laboratory-based studies involving direct age dating of “returned” basaltic lunar samples (from Apollo and Luna missions, and lunar meteorites) by radiometric techniques have yielded much narrower age ranges for mare volcanism, typically in the time interval of 3.9 to 3.1 Ga [14]. Recently, a number of chronological investigations of basaltic lunar samples have revealed crystallization ages which are older, as well as, younger, than previously known range for mare basalt ages [4, 15]. Cryptomaria are mare-basalt deposits whose low-albedo signature has been hidden or obscured by superposed high albedo material. These deposits are assumed to represent an earlier phase of mare volcanism predating the main phase of basin-filling mare deposits that formed between 3.9 to 3.1 Ga. Direct samples of cryptomare have been lacking or were difficult to identify in the lunar sample collections. However, recent age dating of a VLT mare-basaltic meteorite, Kalahari 009, which has a crystallization age of 4.35 Ga [4] provides an increasing evidence that mare basalt magmatism started as early as 4.35 Ga; only ~ 150 Ma after the accretion and differentiation of the Moon. At the other extreme, a ~2.8 Ga crystallization age for lunar meteorite NWA 773 suggests that basaltic volcanism on the Moon occurred over a protracted period of time covering at least an interval > 1 Ga [15].

4. New insights into crustal evolution on the Moon

The lunar highland crust is thought to have formed by the crystallization and flotation of plagioclase from a lunar magma ocean (LMO) although the actual mechanisms are still debated. The composition of the lunar highland crust is therefore important for understanding the formation of LMO and the subsequent evolution of the Moon. The Multiband Imager (MI) on the Kaguya spacecraft measured the composition of the lunar crust at a very high spatial resolution [2]. Otake et al. [2] reported the global distribution of rocks of high plagioclase abundance (approaching 100 vol. %), using an unambiguous plagioclase absorption band recorded by the MI. If the upper crust indeed consists of nearly 100 vol.% plagioclase, this is significantly higher than previous estimates of 82–92 vol.%, providing a valuable constraint on models of LMO evolution.

5. Summary and the future of lunar exploration

Recent advancements in lunar science have undoubtedly heralded a new era of lunar exploration. This, combined with the emergence of new space faring nations with ambitions to explore our nearest planetary neighbour, both robotically and through manned missions, has re-energized the lunar community. The discovery of lunar water has excited explorers and scientists alike for obvious resource implications and for understanding the origin, source, and the quantity of water on the Moon; only the first few questions that can only be answered by further exploration of the Moon, preferably through multi-national collaborative efforts.

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