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Origins of Lunar Water Ice: Analyzing Isotope Signatures and Evidence from Satellite Observations

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Abstract: The discovery of water ice on the moon has revolutionized our understanding of lunar science and has profound implications for future space exploration and habitation. Through a comprehensive analysis of remote sensing data, isotopic studies, and neutron detection experiments, this research elucidates the presence, distribution, and origins of lunar water ice. Radar observations from missions like Clementine and Chandrayaan-1 reveal distinct polar regions with elevated circular polarization ratios, indicative of volatile ice deposits. Spectral detections by instruments such as M3 and Diviner further confirm the presence of water ice in lunar-shadowed regions, with estimates suggesting reserves of up to 300 million tons at the poles. Neutron detection experiments on lunar orbiters like LRO provide additional evidence, detecting hydrogen signals consistent with water ice below the lunar surface. Isotopic analyses offer insights into the origin and evolution of lunar water ice, with comparisons to cometary and asteroidal sources. Proposed missions, such as Artemis-3 and Artemis-4, aim to collect samples from the lunar South Pole for detailed isotopic analysis, furthering our understanding of lunar water ice's composition and history. Scientific data, including the lunar bulk water content and estimated water ice reserves, underscore the significance of lunar water ice as a critical resource for future space exploration endeavors. Calculations estimating the total water-ice area and water abundance near specific lunar features provide valuable insights into the potential utilization of lunar water ice for sustained human presence on the Moon and beyond.

Keywords: lunar polar craters; lunar magma ocean (LMO); D/H ratio; carbonaceous chondrite asteroids; lunar apatite

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Introduction

The presence of water ice on the Moon has sparked great interest in the potential implications for future space exploration and habitation. Water is a fundamental component in the physical and chemical properties of magmas, minerals, and melts and can significantly affect volcanic processes (Anand, 2010). However, the fact that there is water inside the moon goes against the high-temperature models of how it formed and changed over time. These models say that a big impact created a protolunar disk (Hauri et al., 2017) of vaporized matter, which then formed a fully solidified satellite covered in a magma ocean. Nevertheless, previous research suggests that the water content of lunar apatite varies (Robinson et al., 2016) across different rock types.

In 1961, Watson et al. introduced the idea of water ice at the lunar poles. The Moon's rotation axis has a slight tilt of 1.6° (Jia et al., 2023), causing certain polar craters to remain in perpetual darkness, resulting in frigid temperatures. The impact craters in the lunar polar region could potentially hold a significant concentration of water within the ice and dust. The hydrogen and oxygen isotopes are crucial for the significant formation of lunar water. Most of the hydrogen in the universe was formed during the Big Bang (McCubbin & Barnes, 2019) at 13.78 ± 0.06 Ga.

Researchers have discovered two types of water on the moon: water ice in the shadow regions of the lunar poles and interior water found in lunar material (Jia et al., 2023). Comet impacts, meteorites, and the interaction of solar wind protons with oxygen-containing moon surface materials

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combine to form the water ice in the shadow areas (Luchsinger & Chanover, 2022). Various other factors, such as volcanic outgassing and the hydration of the regolith, contribute to the presence of water on the moon (Jia et al., 2023). These findings provide compelling evidence for the existence of water on the moon.

Recent findings (Anand, 2010) based on Apollo samples and spacecraft observations present compelling evidence that the moon was much wetter than previously believed. These discoveries overturn more than four decades of accepted knowledge and force researchers to re-examine their theories on how the moon formed following a high-energy impact. Furthermore, they raise questions about how the molten lunar body was able to cool and accumulate water both inside and outside. The Moon Mineralogy Mapper on the Chandrayaan-1 spacecraft found a changing OH/H2O absorption signature (Luchsinger & Chanover, 2022) on the Moon's surface in 2009. This was a huge step forward in the study of water ice on the moon. The presence of H2O is crucial for setting up a lunar colony and conducting future space explorations.

Figure 1. The image depicts the distribution of surface ice at the moon's poles, detected by NASA's Moon Mineralogy Mapper instrument. Blue areas show the presence of ice, overlaid on an image of the lunar surface, where grayscale represents surface temperature. The coldest, darkest regions, primarily within the shadows of craters, concentrate ice. This groundbreaking observation marks the first direct evidence of water ice on the Moon's surface, offering valuable insights into lunar science and potential resource availability for future exploration endeavors. Credits: NASA.

Insights from the Lunar Magma Ocean (LMO), Asteroidal Contributions, and Meteorite Impacts

It is widely accepted among scientists that the Moon underwent a significant phase (Černok et al., 2020) known as the Lunar Magma Ocean (LMO) after its formation. This phase was characterized by the solidification of the moon's magma, resulting in differentiation that shaped the moon's current composition. We believe that any water or other volatiles present in the Moon-forming material underwent transformation, loss, or exchange before incorporating into the Moon's interior, even though the precise details of the depth, timing, and nature of solidification during the LMO remain a topic of ongoing discussion. During the 1990s, radar readings of Mercury's northern polar area showed the potential existence of water ice (Anand et al., 2014), sparking theories about the possible existence of similar compounds at the poles of the Moon.

The data collected (Černok et al., 2020) from lunar samples suggests that the average bulk water content on the moon is about 100 parts per million (p.p.m.). The lunar differentiation phase, lasting from 10 to 200 million years, is believed to have primarily delivered this water (Figure 2). Carbonaceous chondrite asteroids (Barnes et al., 2016) are the primary source of this water-rich content, with potential contributions from Earth's materials. Comets in the Oort cloud or Kuiper belt may have contributed a small quantity of water, but they account for less than 20% of the total water present in the BSM (Dauphas, 2000). There are conflicting conclusions about the water found in lunar samples. While bulk lunar samples (Anand, 2010) exhibit a D/H ratio similar to Earth's, a specific lunar soil sample, labeled 61221, indicates a cometary origin for these volatiles. Furthermore, recent studies have revealed significant variations in the D/H ratio of lunar apatite, with some instances showing values comparable to those found in comets (Figure 2). The moon's meteorite impacts (Hab, 2022) left volatiles like water, nitrogen, and methane (McCord et al., 2011), most of which decomposed and escaped into space. However, Svetsov and Shuvalov (2015) suggest that the polar regions' PSRs may have preserved and accumulated water as ice.

The type of rock determines the amount of water present in lunar apatite. Specifically, the Apollo Mare basalts contain the highest concentration of water (McCubbin et al., 2010; Greenwood et al., 2011; Barnes et al., 2013; Tarte`se et al., 2013), at 7500 ppm, whereas the KREEP-related rocks that are more advanced exhibit lower levels of water, measuring at less than 3000 ppm. When hydrous magma approaches a planetary surface, the melt degasses and loses water, assuming water is present as OH and H2O, as water solubility in magma decreases with decreasing pressure (Robinson et al., 2016).

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Lunar Water Isotope Composition

The isotope composition of lunar water ice offers crucial insights into its origin and evolutionary history, aiding our understanding of the Moon's volatile inventory and its implications for planetary science and astrobiology (McKay et al., 1989).

The study of isotopes, especially deuterium-to-hydrogen (D/H) and oxygen isotopes (e.g., ^16O/^18O), helps figure out where water comes from and how it gets there (Halliday et al., 1989). By comparing lunar water isotopic ratios with those of comets, asteroids, and Earth's water, researchers can infer the origins of lunar water and elucidate its evolutionary pathways (Marty et al., 2009). Isotopic studies also help us understand how things like solar wind implantation, impact delivery (Figure 2), and outgassing from the moon's interiors happen, which makes our knowledge of how the moon's atmosphere changes over time even better (Hauri et al., 2020).

Overall, the investigation of the isotope composition of lunar water ice plays a pivotal role in advancing our knowledge of lunar science and its broader implications for planetary exploration (Li et al., 2021).

Figure 2. This graphic illustrates potential time frames and scenarios for the accumulation of volatiles within the lunar interior. Volatiles may have been incorporated into the moon during its initial formation (a) and/or continuously introduced by impacting bodies throughout approximately 10 to 200 million years during the solidification of the lunar magma ocean (b) and the accreting moon during the several impacts, depending on how the impactors affected the moon's inner body as well as the earth during the initial stages of the planetary formation. It is believed that the formation of water on the moon and earth was primarily due to the high impact of asteroids, comets, and meteorites. The hypothesis on the origin of lunar water is that the moon had a high bombardment (Füri et al., 2014) of some huge celestial body that contains the isotopes H and O, or maybe water itself.

Observational Data

The new remote sensing results show that the entire lunar surface is hydrated, at least during some portions of the lunar day. This water is present either as structurally bound OH or as molecular H2O adsorbed onto the lunar soil grains.

Radar Detection

Circular polarization ratio (CPR) from the radar can characterize lunar surface properties (Fang et al., 2023). Frozen volatiles, like water ice, reflect radar signals with total internal reflection, keeping the original polarization mode. In 1994, Clementine's bistatic radar picked up a big rise in the ratio of right-circular to left-circular polarization (Nozette et al., 1996) at the south pole of the moon, which pointed to the presence of liquid ice that could melt. Similarly, Chandrayaan-1's Mini-SAR observed abnormal echoes in 2010 within impact craters at the lunar north pole, sparking speculation about water-ice presence (Figure 1). Subsequent findings in 2013 by LRO's Mini-RF at the Shackleton impact crater supported this, indicating water ice covering 5–10 wt% of the lunar soil surface (Jia et al., 2023).

Spectral Detection

In 2009, Chandrayaan-1's M3 detected 2.8 to 3.0 μm absorption features, indicative of hydroxyl or water presence on the lunar surface. The LCROSS impact in 2009 confirmed lunar water, with a 5.6 ± 2.9 wt% estimate. In 2015, Diviner and Lyman Alpha Mapping Project data suggested exposed water ice in lunar polar shadow pits. Li et al. (2018) identified unique near-infrared absorption peaks at 1.3, 1.5, and 2 μm, confirming water ice at the lunar poles. In 2020, Hannibal detected a 6 μm water radiation band near the Clavius impact crater, estimating a water abundance of 100–400 μg g−1 or 355 cm3 per m3 of lunar soil. Davidsson and Hosseini in 2023 proposed that the roughness of the lunar surface shelters water ice, aided by the exosphere.

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Neutron Detection

Neutrons encountering a high hydrogen content on the lunar surface slow down, becoming thermal neutrons (energy < 0.3 eV). LP neutron spectrometer data revealed hydrogen signals at the lunar poles, indicating a water-ice presence approximately 40 cm deep. An estimated total water-ice area at both poles is 1,850 km2 (Feldman, 1998), with a reserve of 300 million tons. The LRO's low-energy neutron detector found hydrogen in the Cabeus and Shoemaker impact craters in the moon's permanent shadow regions. This supported the idea that water exists.

Laser Detection

In 2017, Fisher et al. connected LOLA albedo data with Diviner's surface temperature data. They found that LOLA albedo rose quickly below about 110 km near the south pole of the moon, at the same time that surface water-ice sediments stayed put. In 2019, Qiao et al. analyzed LOLA's 1,064-nm reflectance data, finding brighter permanent shadows on flat surfaces, suggesting widespread water-ice presence (Jia et al., 2023).

Figure 3. (a) Molecular water refers to 2H atoms bonded with 1 oxygen atom. A trillion billion water molecules exist in a 1-milliliter drop of liquid. (b) It is water ice, i.e., an organized, hexagonal crystalline structure that makes water into its solid form. The Lunar Reconnaissance Orbiter (LRO), the LCROSS spacecraft, and telescopes on Earth detected a plume when the ersatz meteorite impacted.

Future Exploration Missions Are Important

The proposal suggests that the Artemis-3 and Artemis-4 missions should gather water ice samples from the Moon's South Pole and return them to Earth for analysis. The goal of this analysis is to determine the origin of lunar water ice by measuring the ratios of oxygen-16 to oxygen-18 isotopes.

Conclusions

The discovery of water ice on the Moon has ignited a change in basic assumptions in lunar science, with profound implications for future space exploration and habitation.

This essay has explored various facets of lunar water ice, from its origins and distribution to the methods used for its detection and characterization. Through a combination of remote sensing, spectroscopic, and neutron detection techniques, scientists have uncovered compelling evidence for the presence of water ice in the shadowed regions of the lunar poles. Radar data from missions like Clementine and Chandrayaan-1, along with spectral detections by instruments such as M3 and Diviner, have provided crucial insights into the abundance and distribution of lunar water ice. Additionally, neutron detection experiments on lunar orbiters like LRO have confirmed the presence of hydrogen signals consistent with water ice at the lunar poles.

Isotopic studies have further deepened our understanding of lunar water ice, offering insights into its origin and evolutionary history. By analyzing the isotopic composition of lunar water ice, researchers can infer its sources and the processes involved in its formation and delivery. This has led to the proposal of missions like Artemis-3 and Artemis-4 to collect samples of lunar water ice from the South Pole for detailed isotopic analysis, aiming to unravel the mysteries of lunar water's origin.

Looking ahead, continued exploration and analysis of lunar water ice hold immense promise for advancing our understanding of the Moon's volatile inventory and its broader implications for planetary science and astrobiology. By leveraging the latest advancements in remote sensing and sample return missions, scientists are poised to unlock further secrets of lunar water ice, paving the way for future lunar exploration and colonization endeavors. Furthermore, the discovery of water ice on the Moon marks a transformative moment in our exploration of the lunar surface, with farreaching implications for humanity's quest to understand the mysteries of our celestial neighbor and beyond.

Scientific Data

Lunar bulk water content: approximately 100 parts per million (ppm).

Estimated water ice reserve at the lunar poles: up to 300 million tons.

Ratio of right-circular to left-circular polarization at lunar poles: an indicator of volatile ice presence.

Estimated total water-ice area at the lunar poles: 1,850 km2.

Water abundance near Clavius impact crater: estimated at 100–400 µg g−1 or 355 cm3 per m3 of lunar soil.

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