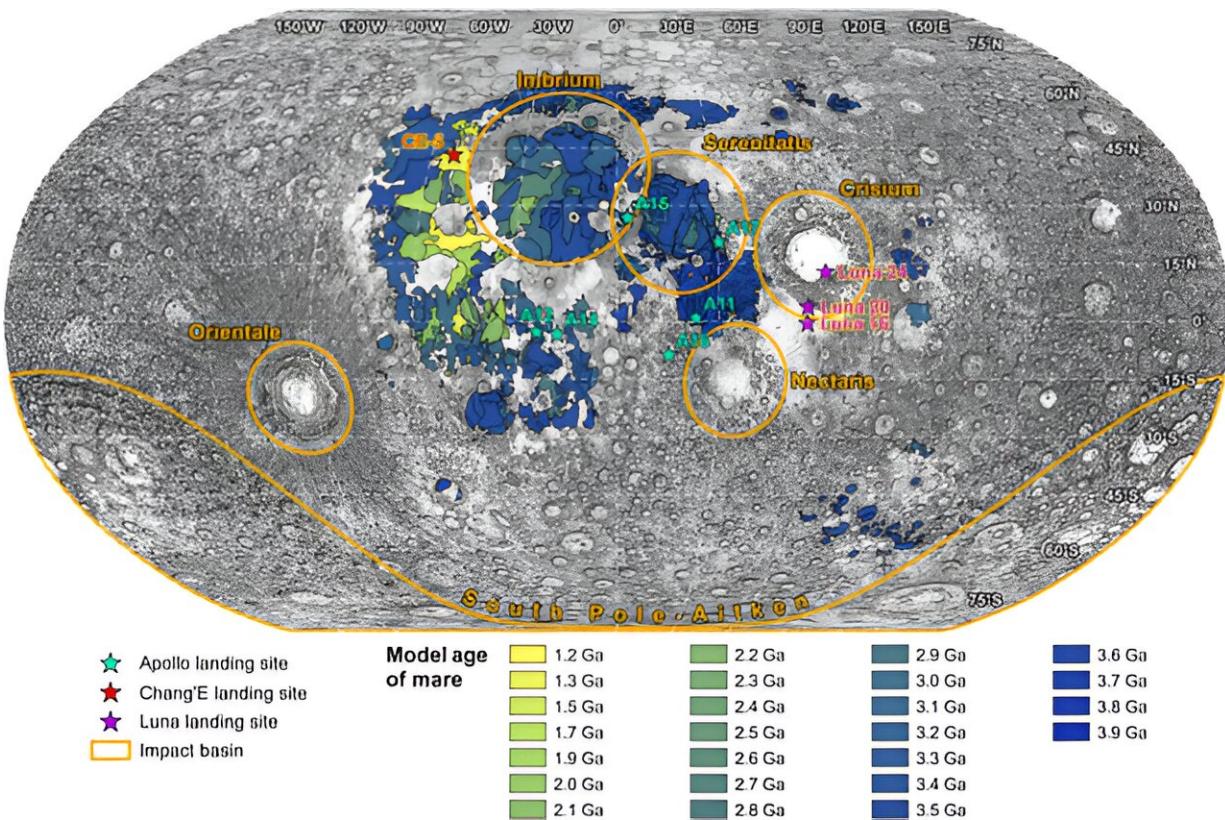


Scholars review lunar crater chronology and impact flux

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Locations of samples returned from the Moon. Model ages of mare deposits [1] were based on superposed crater densities and the Neukum crater chronology [23]. The Moon had a much higher impact flux before the visible lunar mare were emplaced, but the early impact history is largely unconfirmed. Formation ages of several critical impact basins such as those annotated in the figure are critical to evaluate the early impact flux [56]. The base image is a shaded relief model (vertical exaggeration of 8) based on the global digital elevation model constructed using Lunar Orbiter Laser Altimeter data. Credit: Space: Science &

Technology

Scholars reviewed the existing anchor points and construction history of lunar crater chronology. Before the return of lunar samples, the stratification of the near side of the moon was based on remote sensing data from ground-based telescopes and lunar orbiters. Six manned missions and four robotic missions have so far brought back samples, including basalts and volcanic glass, from different geological units of the moon.

Based on the lithology and thermal history of these samples, radiometric dating techniques have determined their radiometric ages, which are then used to interpret the exposure ages of geological units. However, geological background investigations of lunar samples revealed uncertainties due to unclear sample origins and difficulties in deriving crater groups.

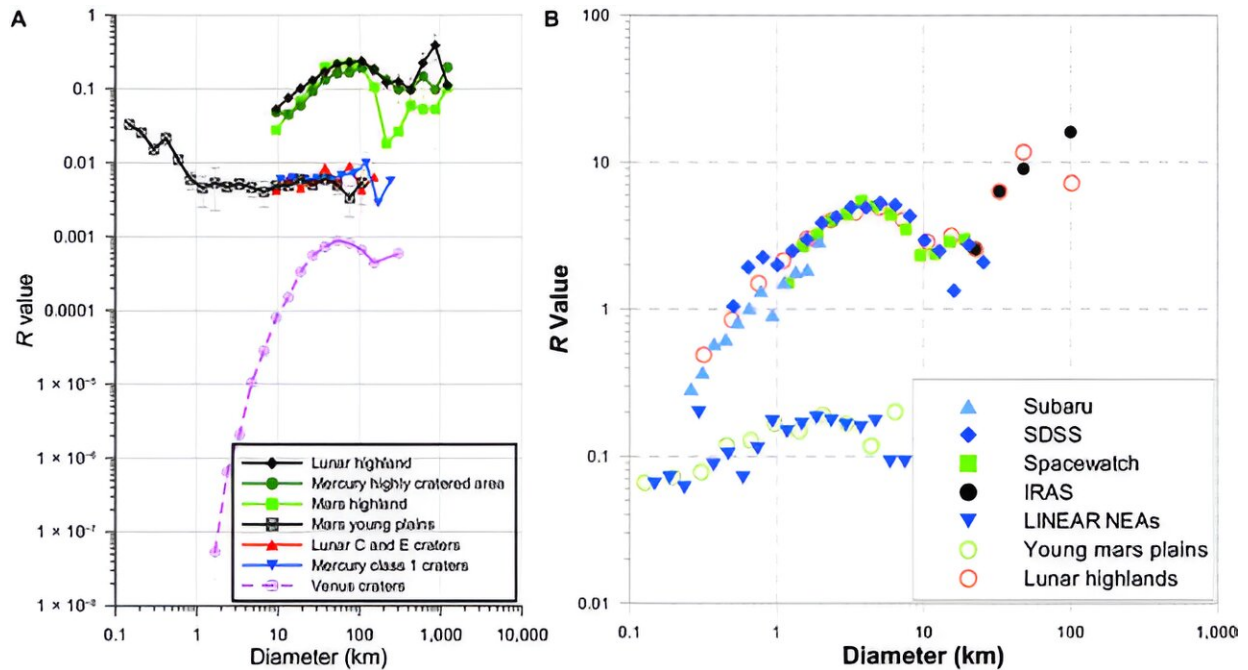
The mixed nature of the regolith makes the geological relationship between samples and specific geological units unclear. Impact craters play a crucial role in estimating the model ages of geological units on the moon and other solid bodies in the solar system. Scholars typically fit mathematical functions to establish lunar crater chronology functions, which predict the model ages of geological units on the moon and other solid solar system bodies.

These predictions are validated by samples returned from deep space exploration missions. For example, samples returned by the Chang'e-5 mission further validated the reliability of age determination techniques based on crater statistics, thereby supporting the current popular lunar crater chronology model.

The article then introduced the main consensus and findings regarding lunar impact flux. Firstly, the lunar impact record began during the solidification phase of the lunar magma ocean. Early impacts did not leave clear records due to the continuous differentiation of the magma ocean. After the magma ocean had mostly solidified around 4.46 billion years ago, the lunar impact structures started to be preserved.

Secondly, the unexpectedly high content of highly siderophile elements (HSEs) in the lunar mantle suggests that the moon continued to be bombarded by chondritic meteorites after the differentiation of the magma ocean, possibly due to a late veneer impact event.

Thirdly, the comparison of crater densities between the lunar highlands and maria indicates that the moon experienced a late heavy bombardment event, with the impact flux significantly higher around 3.8 billion years ago compared to later periods. The South Pole-Aitken (SPA) basin, believed to be one of the largest impact structures on the moon, possibly formed around 4.3 billion years ago. This was followed by the late heavy bombardment (LHB) period around 3.8 billion years ago, which led to significant geological and biochemical evolution on the moon and terrestrial planets.



Similar sources of impactors of inner Solar System bodies, but different crater populations and impactors before and after ~ 3.8 Ga. This figure is adapted from Strom et al. [12]. (A) SFD of crater populations formed on terrains older and younger than 3.8 Ga on the Moon and terrestrial planets. (B) SFD of impactors that formed the crater population in the lunar highland (red circles) and that in the Mars northern plains (green open circle). The older impactor population is comparable with the current main belt asteroids, and the younger impactor population is comparable with the near-Earth asteroids (NEAs). Subaru, SDSS, Spacewatch, IRAS, and LINEAR are telescopes for asteroid observations [12,13]. Credit: Space: Science & Technology

Lastly, since around 3.8 billion years ago, the lunar impact flux has remained relatively stable, with occasional peaks but no significant changes in overall stability. These findings are crucial for understanding the evolution of the moon and terrestrial planets.

Then, the article introduced the main disagreements and significant

progress in resolving the controversy surrounding the impact flux around 3.8 billion years ago. The primary uncertainty in lunar impact flux arises from the mismatch between radiometric ages and model ages predicted by crater chronology. This uncertainty mainly stems from the imperfect calibration of radiometric ages and crater production statistical data, which is common for geological units older than approximately 3.92 billion years, with diameters greater than 300 kilometers or less than about 10 meters.

Additionally, there are other issues such as the precise isotopic ages of returned samples not clearly indicating their source; the unclear origins of early lunar impact events and orbital dynamics; the possibility that the late veneer may have formed after the solidification of the lunar magma ocean, but its specific origin remains uncertain; early lunar impact history providing constraints on the final stages of planetary formation, potentially related to the orbital dynamics of the entire solar system; the uncertain relationship between the lunar late mantle and late heavy bombardment events, making it difficult to attribute early geophysical and geochemical characteristics to specific geological contexts.

The crater groups in the lunar highlands resemble modern main-belt asteroid impactors, suggesting that the main asteroid belt could have been the primary source for impacts on the [moon](#) before 3.8 billion years ago. However, the source and dynamics of early impactors remain uncertain and require further research to resolve these issues.

Finally, the authors summarized the current research and discussed future research directions in the context of planned sample returns. While techniques such as sample analysis, high-resolution geological mapping, geophysical surveys, and orbital dynamics modeling can reduce uncertainties related to unclear sample origins and challenges in deriving crater groups, they have not fundamentally addressed the weak understanding of early meteorite impact processes.

Currently, calibrating lunar impact flux based on sample and [crater](#) structure remains elusive. However, in the coming years, with upcoming lunar exploration missions from various countries set to return more samples and remote sensing data, future research will prioritize sampling sites older than 3.92 billion years. This approach aims to connect planetary evolution and orbital dynamics, resolve early impact history, and further enhance understanding of lunar impact flux.

By designing new exploration missions and research strategies, advancements are expected in calibrating lunar impact flux and elucidating early meteorite impact processes.

The findings are [published](#) in the journal *Space: Science & Technology*.

More information: Zhiyong Xiao et al, Impact Flux on the Moon, *Space: Science & Technology* (2024). [DOI: 10.34133/space.0148](https://doi.org/10.34133/space.0148)

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