Using the Moon to Explore the Entire Solar System

David A. Kring
Universities Space Research Association

Synopsis: The Moon is the best and most accessible place to explore the origin and evolution of the entire Solar System, including the earliest evolutionary phase of our own planet, Earth, a period of time that has since been erased from the surface of the Earth. The Apollo program taught us that the dominant geologic process affecting the surfaces of planets is impact cratering. It has the capacity to affect the geologic and biologic evolution of a planet. Moreover, the impact cratering record provides the clock used to determine the ages of geologic processes on Mars and elsewhere. Variations in that flux of debris can also be used to trace the accretional and orbital evolution of material throughout the solar system, including the distant gas giants in the outer solar system. A compelling case can be made that the Moon is the shortest and least expensive route to a fundamental change in our understanding of our origins.

Apollo Legacy: One of the grand intellectual legacies of the Apollo program is the suggestion that the Earth-Moon system was severely bombarded 4 billion years ago in an event called the lunar cataclysm. Samples collected during the Apollo era suggest impact bombardment of the lunar surface was particularly intense early in solar system history [1]. Argon-Ar isotopic analyses of Apollo samples suggested three to possibly six of the immense impact basins on the nearside were produced between 3.88 and 4.05 Ga [2]. Additional U-Pb and Rb-Sr analyses of Apollo samples suggested the entire lunar crust was metamorphosed by a large number of impactors ~3.9 Ga in what was called the lunar cataclysm [3; see also 4-7]. Testing this hypothesis and determining the magnitude of any cataclysmic bombardment is one of the primary goals for future lunar missions, because the bombardment may have had a profound effect on the entire inner solar system, including Earth.

The Origin and Evolution of Life on Earth: If the lunar cataclysm hypothesis is correct, then it implies at least 20,000 impact craters with diameters >20 km were produced on Earth at the same time, including ~40 impact basins ~1000 km in diameter and several with diameters of ~5000 km [8]. These impact events resurfaced the Earth, dramatically altered the atmosphere, and made surface conditions episodically inhospitable, while simultaneously producing vast subsurface hydrothermal systems that may have been the critical crucibles necessary for pre-biotic chemistry and habitats for the early evolution of life [9-12]. The possible role of impact cratering in the origin of life is enhanced by the near-coincidence of the bombardment and the earliest isotopic evidence of life on Earth (~3.85 Ga [13]) (Fig. 1). In addition, genetic analyses suggest the first organisms or community of organisms on Earth had thermophilic affinities [14,15], which are the types of organisms that would have thrived in impact-generated hydrothermal systems.

An Inner Solar System Cataclysm: There are hints that the lunar cataclysm was actually an event that resurfaced planets throughout the inner solar system [16,8]. Meteoritic fragments from the asteroid belt indicate objects between 2 and 5 AU were shock-metamorphosed between ~3.5 and 4.0 Ga. Furthermore, our first sample from the ancient cratered highlands of Mars (meteorite ALH84001) was shock-metamorphosed 3.92 Ga [17]. Thus, the process first detected on the Moon may have greatly affected all inner solar system planets.

Source of Impacting Objects: Rare geochemical fingerprints of impactors in the Apollo impact melts suggest the impacting objects were dominantly asteroids, rather than comets or Kuiper Belt objects [8]. In addition, the size distribution of impact craters on the Moon seems to require impactors with a size distribution similar to that seen in the asteroid belt [18].

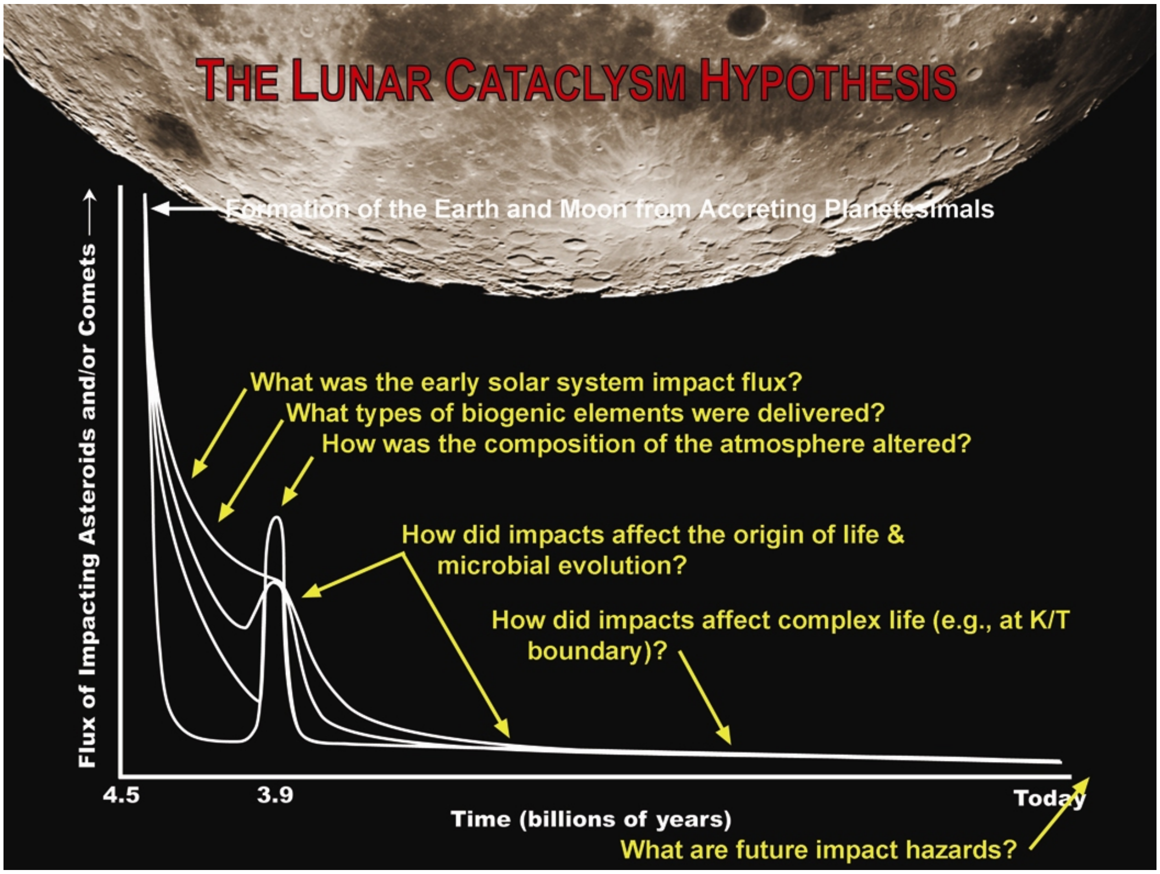

Fig. 1. Schematic diagram illustrating the flux of asteroids and comets that hit the Earth-Moon system. Apollo samples suggest there may have been an intense period of impact bombardment about 3.9 billion years ago, but the amount of data is small. Because of the profound implications that a burst of impact bombardment have for the evolution of Earth and other planets throughout the solar system, this is one of the highest science priorities for lunar exploration and, arguably, for all of planetary science.

Testing the Hypothesis and Refining the Magnitude and Duration of any Cataclysm: The Apollo program generated a tantalizing hypothesis and subsequent studies of other solar system materials have provided hints of how that process may have unfolded. However, we are still working in a data-poor environment. To test the hypothesis and determine the magnitude and duration of any bombardment, a collection of impact melts unambiguously tied to large craters and basins on the Moon are needed for detailed petrologic, geochemical, and radiometric age analyses. These should be selected to represent the entire distribution of relative stratigraphic ages among basin-forming events, and of lunar geographic locations. The highest priority sample is from the South Pole-Aitken basin, which is one of the oldest and largest basins of uncertain age. If this basin is part of the cataclysm, then the magnitude of the bombardment event is far greater than previously proposed, involving ~3 times the number of basin-forming impact events. These same samples can be used to determine the source of projectiles and their chemical compositions. This data can then be used to calculate the delivery of biogenic elements during the bombardment and the environmental consequences of the impact events [21,8].

Implications for Outer Solar System Evolution: If the bombardment did not begin until ~4.1 Ga or later, then these results will also have dramatic implications for the accretion and orbital evolution of outer solar system planets. For example, if future missions confirm that the asteroid belt was the source of the projectiles and the belt was sampled in a size-independent manner [18], then it will imply that orbital resonances swept through the asteroid belt. This, in turn, will imply the orbit of Jupiter shifted ~500 Ma after solar system formation. This migration may have been produced by either the delayed accretion of gaseous planets and/or the re-arrangement of outer planet orbits [20,18]. Thus, studies of the lunar cratering record will dramatically influence our understanding of how the outer solar system evolved too.

Implications for Planetary Systems Elsewhere: If a relatively brief period of bombardment occurred several hundred million years after solar system formation, then a dusty environment was probably created within the inner solar system. New Spitzer Space Telescope observations of debris disks around other stars suggest that similar dust enhancements are being produced 300 to 700 Ma after star formation [e.g., 21]. Consequently, a better understanding of the collisional evolution of our early solar system will help guide our interpretation of the geologic evolution and potential biologic viability of other planetary systems.

Implications for determining the ages of planetary surfaces: If further exploration reveals that the South Pole-Aitken basin or any other pre-Nectarian basins were involved in the cataclysm, then the ages of inner solar system surfaces older than ~3.9-4.0 Ga cannot be reliably determined using crater counting techniques, because those surfaces are dominated by the cataclysm [18]. Furthermore, if asteroids are the dominant source of the impacting objects on the lunar surface, then impact cratering in the outer solar system involved a different flux of impactors and, thus, the ages of planetary surfaces in that region cannot be accurately determined with a lunar-calibrated scale.

Post-Cataclysm Bombardment: The Chicxulub impact crater and its link to the K/T mass extinction event [e.g., 22 for a review] demonstrate that the post-basin-forming impact flux was still sufficient to cause dramatic biologic upheaval. In addition to the flux of sporadic events, it will be important to determine if there were particularly intense storms of impact activity, hints of which occur in the Achaean, at 800 Ma, and 500 Ma. This requires precise analyses of impact melt ages from a moderate number of post-3.8 Ga impact craters on the Moon and an accurate determination of the relative number of impact events that occur between those absolute benchmark ages. These analyses will allow us to determine the role impact cratering has had in the biologic evolution of Earth (both in terms of mass extinctions and evolutionary radiations), how impact cratering has perturbed the climate, and the hazards other impactors pose for Earth today and in the future.

Conclusions: The surface operations and sample collection of the Apollo program dramatically altered our understanding of solar system history. That legacy has generated several fundamentally important questions regarding the geologic evolution of the Earth-Moon system and other planets in the solar system. It has also generated fundamentally important questions about the origin and evolution of life on Earth and potentially other planets in our solar system (e.g., Mars) and other planetary systems. Because the Moon has an exquisitely preserved impact cratering record, it is the best place in the solar system to study the evolutionary effects of this world-changing geologic process.

Dr. David A. Kring, USRA-LPI, 3600 Bay Area Blvd., Houston TX 77058. 281-486-2110.
kring@lpi.usra.edu

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