EVALUATING THE RELATIVE CONTRIBUTIONS OF ASTEROIDS AND COMETS TO THE INNER SOLAR SYSTEM DURING THE FIRST BILLION YEARS.

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Introduction: The ancient cratered highlands of the Moon provide the best and most accessible record of early bombardment in the Solar System. Samples from the highlands and, in particular, the margins of three nearside basins, reveal a surprising pattern. Their ages are dominantly ~3.9-4.0 Ga, which was interpreted to mean there was an increase in bombardment at that time (e.g., [1,2]) described as a lunar cataclysm. Strictly speaking, the samples only addressed the timing of the latter third of the basin-forming events. The timing of earlier events remain murky.

Testing the lunar impact cataclysm hypothesis is the highest priority science investigation when we access the lunar surface again [3]. The importance of bombardment to the evolution of the Moon and the need to better understand it is echoed in a recent document prepared at the behest of the NASA Associate Administrator for Science [4] and in a re-affirmation of a National Research Council report [3] by the Lunar Exploration Analysis Group [5].

While the magnitude and duration of the bombardment are immensely important, it is the implications those data have that really tug our interest. What caused the bombardment? What was the source (or sources) of the impacting material? What caused it to pummel the Moon and, by inference, the Earth and other terrestrial planetary surfaces? How did that bombardment affect the early evolution of those surfaces and, at least in the case of the Earth, the early evolution of life. Each of those issues is to be addressed in *The First Billion Years: Bombardment* topical conference. In this paper, I address the progress we have made in assessing the sources of the impacting material.

Evolution of Ideas: Because astronauts recovered samples of impact melt from the basin-forming epoch, the samples could be probed for chemical signatures of any projectile material entrained in them. The preferred tracers are siderophile elements, because the Moon's native abundances were sequestered into the core and mantle. Thus, siderophile elements in impact melts produced in the lunar crust are largely derived from the impactors. Kring and Cohen [6] reviewed that data and found impact melts contained signatures of ordinary (OC) and/or enstatite chondrites (EC) and iron meteorites. Importantly, there did not seem to be any trace of CI or CM carbonaceous chondritic materials, which are our best proxies for comets. Thus, they concluded, "Comets were not important during this time."

We then posed another question: Is there a geological fingerprint of the impacting projectiles? The answer is yes – in the form of the size frequency distribution of craters produced in the highlands. In a novel integration of two methods, Strom et al. [7] measured the size frequency distribution of observed craters and then used pi-scaling techniques to evaluate the size frequency distribution of projectiles that produced them. While the impact parameters for any individual impact can vary, the values for the entire population can reasonably be assumed average (e.g., with a 45 degree impact trajectory). The calculated size frequency distribution matched that of main belt asteroids and not that of comets and Kuiper Belt Objects known at that time. It is important to note that the population of the largest basins is small, which implies greater uncertainty among the sizes of the largest impactors. Nonetheless, based on that analysis, they wrote "Because the impact signature in the crater record in the inner Solar System is asteroidal, we conclude that either comets played a minor role or their impact record was erased by later-impacting asteroids." Our unpublished analysis of the size frequency distribution indicated <15% of craters were produced by comets.

Attention then turned to the lunar regolith. Could fragments of the impactors have survived and be found as relics in ancient lunar soils? In ancient regolith samples, Joy et al. [8] detected relics with affinities to carbonaceous chondrites (CC) and properties distinct from comets. The lack of detectable comet fragments indicated <5 to 17% of the impactors could be comets, leading them to conclude "the impactor relics described here indicate that asteroids were the dominant objects hitting the Earth-Moon system at the end of the basin-forming epoch and that the flux of comets was small." The study also showed the types of impactors diversified after the basin-forming epoch ended.

Those studies collectively suggested the relative contribution of asteroids and comets during the basin-forming epoch, or at least the latter part of the basin-forming epoch, was dominated by asteroids. Can we probe deeper in time?

An obvious target for that question is water, which had, in the midst of the studies above, been detected in lunar samples [9] and, thus, inferred to be present in the lunar interior. Water in asteroids and comets has sub-equal abundances and distinct isotopic compositions. Two questions followed. When did that water accrete to the Moon? What was the source of that water? Several teams addressed one or both of those questions. Saal et al. [10], Füri et al. [11], and Barnes et al. [12] determined that the water had affinities to asteroidal CC, although Greenwood et al. [13] preferred a cometary origin. Barnes et al. [12] went on to write "…we conclude that comets containing water enriched in deuterium contributed significantly <20% of the water in the Moon." They also argued most of the water was delivered before the Moon's crust solidified. If true, the asteroids delivered water to the Moon in its initial ~200 million years of evolution.

Dynamical Insights: The geological record of bombardment [7] has implications for the dynamical origin of the bombardment. Because the size frequency distribution of calculated projectile diameters matched that of main belt asteroids, the asteroid belt must have provided projectiles in a size-independent manner. That suggests gravitational resonances swept through the asteroid belt. That implied, in turn, that the orbits of Jupiter (and other giant planets) evolved.

In parallel with the geochemical, isotopic, and geological studies described above, several dynamical models for early Solar System evolution were being developed. Gomes et al. [14], for example, proposed an instability caused giant planets to migrate, which had the advantage of increasing the proportion of asteroids delivered to the inner Solar System over previous models [15]. The parameter space for those dynamical models continues to be explored (e.g., [16-18]), as discussed in separate papers at the conference.

New Directions: The work of [7] prompted a hypothesis: If resonances were sweeping inward, could we detect the early production of impactors from the outer belt, followed by impactors from the inner belt? Thus began an examination of the geochemical and isotopic fingerprints of impactors in lunar impact melts as a function of their age using new analytical techniques developed by Walker's group [19-21] and others. Their data are broadly consistent with a diverse set of chondritic impactors and an additional contribution from a fractionated core-composition impactor, although Fischer-Gödde and Becker [22] suggest the diversity is, instead, a mixing trend between a CC component and a type IVA iron meteorite component. If the compositions of Liu et al. [21] reflect multiple impactors rather than mixing, then compositions change from CC affinities at 4.2 Ga to OC and EC affinities at 3.75 Ga, which might be reflecting sweeping of resonances as postulated by [7] from the outer to inner portions of the asteroid belt. In the midst of that sweep, impactors with iron meteorite affinities occur, which could have been scattered from the terrestrial zone and deposited in the midst of the asteroid belt before the resonances moved. Materials with geochemical and isotopic affinities to OC and EC, along with type IAB irons, are also important components in the local feeding zone of the accreting Earth [23].

Conclusions: There sometimes appears to be a tangle of evidence, in part because of the challenge to separate sources during accretion (both before and after the giant impact, both before and after core formation) and subsequent impacts (both before and after lunar crust formation). A comprehensive solution eludes us. While it will be productive to continue probing the existing collection of lunar samples and explore dynamical models that may have delivered the projectiles, it is clear that substantial, potentially transformative [4], progress can be made if/when we collect new samples from the Moon at specifically targeted sites and return them to Earth for detailed analyses. It will be enlightening, for example, to determine the age and nature of the projectiles that produced the oldest basin (South Pole-Aitken basin) and one of the youngest basins (Schrödinger and Orientale). As has been explored elsewhere (e.g., [24]), a mission to the Schrödinger basin has the potential to provide all of those answers.

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