NEW INSIGHTS OF EARLY BOMBARDMENT PROCESSES FROM ACCRETION THROUGH THE BASIN-FORMING EPOCH. David A. Kring[1,2], Timothy D. Swindle[3,2], and Richard J. Walker[4,2], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston, TX 77058, kring@lpi.usra.edu, [2]NASA Lunar Science Institute, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, [4]University of Maryland, College Park, MD 20742.

The Accretional Epoch: We begin with the discovery of a fragment of rock that survived a collision among planetesimals that occurred during the accretion of Earth and prior to the formation of the Moon. The MIL 05029 meteorite is an impact melt breccia that was produced in a collision ~4.54 Ga that created a 25-60 km diameter crater and shattered the interior of the 100-200 km diameter L-chondrite parent body [1]. In a similar study, we had previously shown that the Portales Valley meteorite was produced beneath the floor of a >20 km diameter crater on the 150-200 km diameter H-chondrite parent body [2] in an event that occurred >4.46 Ga [3]. Other collisions during the accretional epoch have been detected on the E-chondrite (~4.53 Ga), IAB (>4.47 and perhaps >4.52 Ga), HED (~4.48 Ga), and L-chondrite (4.46 and 4.43) parent bodies ([4] and references therein). Collectively, these data indicate sizeable impact events were occurring among planetesimals as the accretional phase wound down and the largest planetary collisions (e.g., the Moon-forming giant impact) were occurring.

The Magnitude and Duration of the Lunar Cataclysm: After the Moon accreted, there may have been a significant decline in the impact flux between ~4.4 and ~4.1 Ga because there are very few impact ages within that interval. In contrast, there are large numbers of ~4.0-3.8 Ga impact ages in samples collected around the Apollo landing sites [5,6]. That data imply a severe period of bombardment that has been called the lunar cataclysm. Additional analyses of impact melts that were extracted from lunar meteorites (and, hence, come from other locations on the Moon) are consistent with that interpretation [7,8].

The canonical lunar cataclysm is defined by ~15 basin-forming impacts that occurred during the Nectarian Period and Early Imbrian Epoch. Nearly 30 additional basins were produced during the pre-Nectarian on the Moon, but they were not sampled during Apollo. It is not yet clear if they were produced during the the same cataclysmic surge of cratering events and they are, thus, targets of future lunar missions [e.g., 9].

Sources of Impactors: Siderophile signatures of impactors are entrained in lunar impact melts and suggest the impactors were dominated by asteroids rather than comets ([10] and references therein). Recent analyses of Apollo 17 specimens [11,12] indicate a pre-Serenitatis impactor (>3.89 Ga) had affinities with ordinary chondrites, the Serenitatis impactor (~3.89 Ga) was a chondritic asteroid (but unlike any meteorites in our current collection from the asteroid belt), and that a post-Serenitatis (~3.75 Ga) impactor had affinities to enstatite chondrites or, marginally, ordinary chondrites. Interestingly, these data imply there were more ordinary chondrite planetesimals than those currently represented by the LL, L, and H groups of meteorites.

A completely independent assessment of the impactors can be derived from the size distribution of the lunar basins and smaller craters in the ancient cratered highlands of the Moon [13]. That analysis suggests asteroids dominated the flux and that the asteroid belt was sampled in a size-independent fashion. That latter observation implies resonances swept through the asteroid belt and that Jupiter's orbit shifted.

That same method was recently used to probe the crater size distribution further ([14] and Marchi et al., this workshop). That study discovered a shift in the size distribution of craters that implies a shift in the impact velocities of impacting asteroids. At some point between the formation of the South Pole-Aitken and Nectaris basins, impact velocities may have roughly doubled. This is consistent with a shift in the orbits of Jupiter and other outer solar system planets that has previously been implied [e.g., 15, 13] for the production of the Nectarian and Early Imbrian basins. It also implies, however, that some of the pre-Nectarian basins, including the South Pole-Aitken Basin, were produced independently through other collisional mechanisms.

A third independent assessment of the source of impactors can be derived from the lunar regolith. A recent study of Apollo 16 samples discovered the first mineralogic and lithologic remnants of projectiles during the latter phase of the basin-forming epoch ([16] and Joy et al., this workshop]. Those results are also consistent with an asteroidal source for the impactors. Indeed, the relics are dominated by fragments of chondrules similar to those in chondritic meteorites.

The Inner Solar System Cataclysm: The Moon has provided an incredibly useful measure of the collisional events that shaped early solar system evolution. Additional evidence has also been gleaned from asteroids, some of which confirms interpretations of lunar data and some of which provides other insights.

A recent analysis of impact melt breccias from the H-chondrite parent body indicate significant collisional activity 4.0-3.5 Ga [17], followed by a sharp decline in the flux of impacting debris. Impact ages in that same 4.0-3.5 Ga interval have been seen in a large number of samples from the HED parent body and in a smaller number of samples from the L and LL chondrite parent bodies [e.g., 18,19,4]. In addition, a major collision involving the IIE parent body occurred ~3.7-3.6 Ga [e.g., 4]. The large number of impact events among asteroids 4.0-3.5 Ga implies the lunar cataclysm is really an inner solar system cataclysm [10].

In almost all cases, the samples being measured come from simple craters and the ejecta around simple craters. Thus, most of the impact events represented by the chondritic samples are smaller than those that produced the lunar basins. (A collision among planetesimals with the same energy needed to produce a lunar basin would completely disrupt the planetesimals.) Thus, collisional age spectra dominated by simple cratering events on chondritic bodies may be similar, but not identical, to the age spectra of basin-size events on the Moon. This is likely one reason chondritic ages range from 4.0-3.5 Ga, while the basin-forming epoch on the Moon ended 3.8-3.7 Ga. It also seems likely that the dynamical situation (asteroids are closer to the source of the impators than the Moon) may produce subtle differences in the age spectra among asteroids and the Moon.

Flux of Asteroids to the Moon: If the lunar cataclysm occurred within 20 to 200 Myr, then the annualized mass flux to the Moon was ~3.5×10^{13} to ~3.5×10^{14} g/yr for a Nectarian and Early Imbrian event [20]. If the pre-Nectarian basins were also involved, then the annualized mass flux was 2.3×10^{14} to 2.3×10^{15} g/yr. Asteroids contain significant quantities of H_2O and other biogenic elements [21]. Recent data [11,12,16] imply chondritic projectiles, some with affinities to enstatite, ordinary, and carbonaceous chondrites. That implies ~6×10^{19} to ~1×10^{21} g of H_2O were delivered to the Moon during the Nectarian and Early Imbrium, and an additional ~3×10^{20} to ~7×10^{21} g of H_2O during the pre-Nectarian, although some of that mass would have been lost from the Moon as high-velocity ejecta. The mass flux to the Earth was at least 13 times greater. While substantial, the canonical cataclysm could not have delivered the entire inventory of Earth's water. A large fraction of Earth's water was delivered during the earlier accretional phase.

Preparing for Future Missions: To further test the lunar cataclysm hypothesis and determine the duration of the basin-forming epoch, we need to recover new impact samples from the lunar surface that have a well-understood geologic context and have properties suitable for complementary analyses of their ages and siderophile content. A series of landing site studies are underway and a leading candidate that has emerged is Schrödinger Basin [22]. This is the second youngest basin on the Moon. It also resides within the oldest and largest basin on the Moon, South Pole-Aitken Basin. Thus, samples within Schrödinger Basin may provide the ages of both basins and effectively bracket the duration of the entire basin-forming epoch.

If the age of samples of the South Pole-Aitken Basin indicate it is part of the lunar cataclysm, then that implies there were ~3 times more basin-forming impacts than in the canonical model. On the other hand, if the age of South Pole-Aitken Basin is much older (consistent with [14]), then pre-Nectarian basins with successively younger relative ages need to be sampled to determine when the cataclysm began. Candidate targets include the Nubium Basin (middle pre-Nectarian), Smythii Basin (slightly younger), and the Apollo Basin (the last of the pre-Nectarian Basins and also within the South Pole-Aitken Basin). The timing of the latter third of the basin-forming epoch and the nature of the projectiles involved will require better documented samples of impact melt or impact-metamorphosed samples from Nectaris, Serenitatis, Crisium, Schrödinger, and Orientale.

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