Bombardment History of the Moon: What We Think We Know and What We Don't Know

Donald Bogard, ARES-KR, NASA-JSC, Houston, TX 77058 (donald.d.bogard@nasa.gov)

Summary. The absolute impact history of the moon and inner solar system can in principle be derived from the statistics of radiometric ages of shock-heated planetary samples (lunar or meteoritic), from the formation ages of specific impact craters on the moon or Earth; and from age-dating samples representing geologic surface units on the moon (or Mars) for which crater densities have been determined. This impact history, however, is still poorly defined.

The heavily cratered surface of the moon is a testimony to the importance of impact events in the evolution of terrestrial planets and satellites. Lunar impacts range in scale from an early intense flux of large objects that defined the surface geology of the moon, down to recent, smaller impacts that continually generate and rework the lunar regolith. Densities of larger craters on lunar surface units of dated age define a projectile flux over time that serves as the basis for estimating surface ages on other solid bodies, particularly Mars. The lunar cratering history may address aspects of Earth's evolution, such as the possible role of early intense impacts on the atmosphere and early life and possible periodicity in large impact events in the more recent past. But, much about the lunar impact history remains unknown..

On Earth approximately 172 impact craters up to ~300 km in diameter and up to ~2 Gyr in age are recognized (1). Although these data suggest greater relative numbers of younger craters, possibly suggesting a recent increase in projectile flux, both the diameters and especially the ages of most terrestrial crates are so poorly known that the differential terrestrial impact flux over time is uncertain.

For the moon, densities of craters on some mare surfaces and crater ejecta deposits, for which we have measured or estimated formation ages, suggest an approximately constant lunar impact rate of larger projectiles over the past ~3.5 Gyr. However, the data are cumulative in nature and limited. Questions exist as to how accurately dated samples correlate with surfaces having measured crater densities. Studies of ages of many tiny impact-melt beads from Apollos 12 and 14 soils show a decrease in the number of beads with age from ~4 Gyr ago to ~0.4 Gyr ago, followed by a significant increase in beads with age <0.4 Gyr (2). These authors concluded that the projectile flux had decreased over time, followed by a significant flux increase more recently. However, this data set has also been interpreted to represent variable rates of impact melt production as a function of regolith maturity (3). In another study, measured ages of 21 small impact melt clasts in four lunar meteorites from the lunar highlands suggested four to six impact events over the period ~2.5-4.0 Gyr ago (4). Clearly considerable uncertainty exists in the projectile flux over the past ~3.5 Gyr and whether this flux has been approximately constant or exhibited appreciable shorter-term variations.

A few dated lunar surfaces older than 3.5 Gyr imply a much higher impactor flux in the earliest lunar history, although we have no direct data prior to ~4 Gyr ago. Dating of returned lunar samples have yielded approximate formation ages of a few major lunar basins, e.g., Imbrium at ~3.85 Gyr and Serenitatis at ~3.87 Gyr. These ages and three additional observations support the idea of a period ~3.8-4.0 Gyr ago when the projectile flux was much higher than either before or after this time. These are: 1) the observation that radiometric ages of many lunar highland rocks were reset in the time period of ~3.8-4.1 Gyr ago; 2) the argument that the mass accreted to the moon by basin-forming projectiles ~3.8-4.0 Gyr ago was too large to extrapolate back into earlier lunar history; and 3) the observation that eucrite meteorites, thought to derive from the ~550 km diameter asteroid, Vesta, show a distribution of K-Ar ages that resembles the distribution of ages of lunar highland rocks. This proposed period of enhanced flux has been called the impact cataclysm or sometimes the heavy late bombardment (5, 6). On the other hand, some workers have argued that this period of a higher impact rate was the tail end of a much higher projectile flux remaining from lunar formation, which continually reset the ages of lunar highland rocks over the period of ~4.4-3.9 Gyr ago (7). These two impact models represent end-member concepts of the projectile flux in the first ~0.8 Gyr of lunar history, and as the time period of an enhanced cataclysm flux becomes longer, the two models tend to merge. Thus, dating the formation ages of the oldest lunar basins and large farside craters, i.e. knowledge of the impact rate in the period 3.9-4.4 Gyr ago, is key to understanding the early bombardment history.

The moon is not the only planetary body to yield data relevant to the early projectile flux in the solar system. Basaltic eucritic meteorites are thought to derive from the large (~550 km) asteroid Vesta. Most eucrites are breccias formed and heated by impact and give Ar-Ar ages ranging over ~3.5-4.1 Gyr (8). Thus the inferred impact history of Vesta appears to be consistent with the lunar chronological data. The eucrite data indicate that an enhanced "cataclysmic" bombardment was not limited to orbital distances near the Earth-moon system, but was longer in time than suggested by the lunar data. Among eucrites, the general lack of reset Ar-Ar ages in the time period of 4.1-4.4 Gyr and the existence of older ages by other radiometric techniques suggests that the projectile flux at Vesta in this time period was relatively low, possibly inconsistent with the Hartmann (7) flux model.

The source and compositions of the early projectiles remain largely unknown. This ignorance extrapolates to early Mars and the Earth, not only for the effects of impactors on crustal characteristics, but also on atmospheric evolution and possibly early life. Were these objects residues from feeding zones during planet formation, possibly implying significant spatial variations? Were impactors scattered objects from the asteroid belt, implying affinities with meteorites? Were they Kuiper belt objects, scattered as the orbits of the outer planets migrated, thus suggesting that they may have been volatile rich and contributed significantly to volatiles on Earth and Mars?

Improving our knowledge of the projectile flux over time requires additional data of three types. One is examining the statistics of radiometric ages of individual planetary samples (lunar or meteoritic) that have been significantly heated by impacts; a second is dating the formation time of specific impact craters on the moon or Earth; and the third is age-dating samples from surfaces on the moon (or Mars) for which crater densities have been determined. In addition, there is the uncertainty of possible spatial differences in projectile fluxes among planetary bodies. For the early lunar period determining the impact history is even more difficult because surface crater densities are often saturated, craters are degraded, and ejecta from such impacts has been heavily reworked, disturbing the chronology. Important new information about the early flux could be gained by dating specific large basins such as South Pole-Aitken, the largest and oldest on the moon, and large craters from the far-side northern highlands, which represents the oldest crust least affected by large near-side basins. Correlating rock ages with chemical type may also be informative. Acquiring the optimum samples for dating is key, but will not be easy.

Possible shorter-term variations in projectile flux over time could be addressed by determining formation times of many (e.g., ~100) lunar craters of small to intermediate size with ages ≤1 Gyr. Such age determinations can be made by radiometric dating of strongly heated or melted ejecta or by determination of near-surface exposure times to cosmic rays, but both methods probably require sample return to Earth. Both methods also require that we definitely associate rocks with a specific crater, which will require that each crater be examined in some detail, either robotically or by humans.

References: (1) www.unb.ca/passc/Impact Database; (2) Culler T. et al.(2000) Science 287, 1785; Levine J. et al. (2005) GRL 32, L15201; (3) Horz F. (2000) Science 288, 2095a; (4) Cohen B. et al. (2005) MAPS 40, 755; (5) Tera F. et al., (1974) EPSL 22, 1; (6) Ryder G. (2002) JGR 107#E4, 1583; (7) Hartmann W. (2003) MAPS 38, 579; (8) Bogard D. (1995) MAPS 30, 244.