The Violent Early Solar System, as Told by Lunar Sample Geochronology

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One of the legacies of the samples collected by the Apollo and Luna missions is the link forged between radiometric ages of rocks and relative ages according to stratigraphic relationships and impact crater size-frequency distributions. Our current understanding of the history of the inner solar system is based on the relative chronology of individual planets, tied to the absolute geochronology of the Moon via these important samples.

Sample ages have enabled us to infer that impact-melt breccias from Apollo 14 and 15 record the formation of the Imbrium Basin, those from the highland massifs at Apollo 17 record the age of Serenitatis, those from the KREEP-poor Apollo 16 site record the age of Nectaris, and materials from Luna 24 record the age of Crisium. Ejecta from smaller and younger craters Copernicus and Tycho were sampled at Apollo 12 and 17, respectively, and local craters such as Cone at Apollo 14, and North Ray and South Ray at Apollo 16 were also sampled and ages determined for those events. Much of what we understand about the lunar impact flux is based on these ages.

Samples from these nearside locations reveal a preponderance of impact-disturbed or recrystallized ages between 3.75 and 3.95 billion years. Argon and lead loss (and correlated disturbances in the Rb-Sr system) have been attributed to metamorphism of the lunar crust by an enormous number of impacts in a brief pulse of time, called the Lunar Cataclysm or Late Heavy Bombardment. Subsequent high-precision geochronometric analyses of Apollo samples and lunar highlands meteorites show a wider range of ages, but very few older than 4 Ga. The paucity of ancient impact melt rocks has been interpreted to mean that either that most impact basins formed at this time, or that ejecta from the large, near-side, young basins dominates the Apollo samples.

The impact history of the Moon has significant implications because the lunar bombardment history mirrors that of the Earth. During the cataclysm, 80% of the lunar surface was resurfaced; on Earth, this would scale to ~23,000 large impacts in a brief time. Impact ages in ordinary chondrites, HED meteorites, and the Martian meteorite ALH 84001 suggest that this early bombardment event affected the entire inner solar system. If true, the late heavy bombardment may have directly affected the evolution of life on Earth and our understanding of "habitable" planets.

Lunar sample ages have also been used to drive large-scale dynamical modeling of solar system formation. These new models of planetary dynamics show a violent beginning to our solar system, where the late formation or outward migration of the gas giant planets destabilizes the Kuiper belt and main-belt asteroids, sending a cascade of impactors into the Moon and all the inner planets. The existence of an early bombardment has even been postulated in extrasolar planetary systems.

Even after 40+ years of study, the provenance of returned lunar samples and ages of key events continue to be a focus of research and a topic of debate. One of the most important lessons learned from Apollo missions is that small samples yield a wealth of information and are gifts that keep on giving. The legacy of Apollo samples serves as a model and impetus for future sample return missions from the Moon, Mars, and asteroids.