PROLONGED EARLY BOMBARDMENT OF THE INNER SOLAR SYSTEM FROM AGES OF LUNAR SAMPLES.

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Introduction: A spike in the flux of asteroid-size bodies impacting the terrestrial planets at 3.9 Ga has become a keystone of recent models describing planetary dynamics, the chronology of planetary surfaces, and assessments of potential habitability of the early environments of Earth, Mars, and exoplanets. Lunar samples provided the initial observational data that motivated this idea, with recent dynamical models invoking orbital migration of the outer planets providing a plausible mechanism. The absence of lunar impact melt breccias with ages older than 4.0 Ga has been cited as evidence favoring the formation of many if not all of the lunar basins during a cataclysmic episode of heavy bombardment. Here we summarize recent evidence from lunar samples that favours a prolonged episode of heavy bombardment, and suggests that the basin-forming epoch on the Moon likely spanned a significantly longer period of time than implied by the Terminal Cataclysm hypothesis.

Impacts dated by lunar zircons: Most lunar zircons formed by igneous crystallization of KREEP-rich magmas, but some appear to have crystallized directly from impact melts and therefore date the timing of impact events directly. Primary impact-melt zircons found in lunar meteorite SAU169 and Apollo 12 impact melt rocks 12032 and 12033 yielded U-Pb ages of 3.91 $\pm$ 0.02 Ga, which probably dates the Imbrium basin-forming event. The commonly quoted 3.85 Ga age of Imbrium based on ^{40}Ar-^{39}Ar dating of Apollo 15 impact melt breccias is in agreement with the zircon age after re-calibration for new monitor ages and revision of the K-Ar decay constants. In contrast, zircons in a siliceous impact melt clast in breccia 73217 yielded a significantly older impact age of 4.34 Ga. Shock recrystallised or amorphic lunar zircons from Apollo 17 breccias date at least four impact events at 4.11, 4.19, 4.31, and 4.33 Ga. These zircons probably date large impacts based on the inferred crystallization depth of the parental magmas and the magnitude of the shock and heating necessary to recystallize lunar zircon.

Pre-Cataclysm lunar impact melt breccias: SHRIMP dating of zirconalite in anorthositic lunar breccia 67955 yielded a U-Pb age of 4.22 $\pm$ 0.02 Ga, in agreement with the ^{147}Sm-^{143}Nd isochron. The texture and presence of meteoritic contamination in this crystalline breccia indicates that it formed by slow cooling of a large body of impact melt. Some lunar granulitic breccias and fragment-laden melt breccia clasts have yield ^{40}Ar-^{39}Ar platueau ages of 4.1-4.3 Ga but the question of partial equilibration of older components has bedeviled interpretations of those data. ^{187}Re-^{187}Os isochrons may provide additional age constraints but so far they do not appear to be a generally applicable to lunar melt breccias.

Summary: It appears that the Moon, and therefore also Mars and Earth, experienced an extended phase of post-accretionary heavy bombardment spanning $\geq$500 Ma rather than a single short, sharp spike of basin-forming impacts at 3.9 Ga. The Late Cataclysm hypothesis in which all lunar basins formed at 3.8-4.0 Ga is increasingly untenable. Possible implications of a prolonged episode of heavy bombardment for the environmental conditions on Mars and the early Earth, and for chronologies based on basin populations may need further consideration.