Apparent Late Heavy Bombardments.

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Introduction: The Late Heavy Bombardment (LHB), a hypothesized impact spike at ~3.9 Ga, is one of the major scientific concepts to emerge from Apollo-era lunar exploration. While it was originally hypothesized based on analyses of Pb isotopes and Rb-Sr ages of a limited set of Apollo samples[1], a significant portion of the evidence now marshalled comes from histograms of ^{40}Ar/^{39}Ar “plateau” ages[2]. Despite the lack of erosion and plate tectonics, the lunar crust does not retain a perfect impact record due to protracted crust formation, lunar volcanism, and overprinting from subsequent impact events. Indeed, virtually all Apollo-era samples show ^{40}Ar/^{39}Ar age spectrum disturbances due to later re-heating events[3]. This provides evidence that partial ^{40}Ar resetting is a significant feature of lunar ^{40}Ar/^{39}Ar analyses which could bias interpretation of bombardment histories due to “plateau” ages being misleadingly young. In order to examine the effects of partial reseting on the inference of bombardment histories from “plateau” ages, we combine chronologic information derived from the early heating steps of each ^{40}Ar/^{39}Ar analysis, as this represents a good approximation of the timing of the last reheating event, with a first-principles physical model of ^{40}Ar* diffusion in Apollo samples. We use this modeling framework and data compilation to examine the uniqueness of inverting “plateau” age histograms from synthetic impact histories as implemented in two models with differing assumptions about ^{40}Ar loss during impacts.

Methods: Specifically, we compiled the initial step-heating ages for 267 analyzed Apollo samples and interpret them to represent the timing of the last re-heating event (termed Last Heating Ages; LHA). We utilize LHAs as our primary constraints on the shape of the impact history because they reveal the age of the least retentive portion of the sample and are therefore unlikely to be partially reset. Our diffusion model contains 1,000 synthetic ‘samples’ with initial ages drawn from the distribution of lunar ^{207}Pb-^{206}Pb zircon ages and trials random impact histories to recreate a distribution of LHAs. Since we have no prior information for the distribution of fractional loss of ^{40}Ar in an impact, we utilize two separate models to examine the effect on the inferred impact history of a range of assumptions. In our first model run we utilize a uniform distribution of fractional loss and compile a histogram of “plateau” ages. In the second model we explicitly constrain it to create LHB at either 3.9 Ga or 4.1 Ga and instead fit a probability distribution of fractional loss for ^{40}Ar in each impact event.

Results and Discussion: We find that both our models produce good fits to the LHA distribution. Model 1 is only constrained to the LHAs and produces a “plateau” histogram with a broad bombardment episode between 3 and 4 Ga. While Model 1 does not reproduce the LHB in detail, the fact that it produces an impact spike shows that “plateau” histograms are likely prone to suggesting late bombardments. Our model 2 was able to both fit the LHA distribution and create an apparent LHB at either 3.9 Ga or 4.1 Ga. Our results show that “plateau” histograms tend to yield age peaks, even in those cases where the input impact history did not contain such a spike. That is, monotonically declining impact histories yield apparent episodes that could be misinterpreted as an LHB-type events. Since not only Apollo samples show apparent impact spikes, but the H-chondrites and HED meteorites do as well[4], our findings have broader implications to impact histories for meteorite parent bodies. We conclude that the assignment of apparent “plateau” ages bears an undesirably high degree of subjectivity. When compounded by inappropriately simplistic interpretations of histograms constructed from such “plateau” ages, impact spikes that are more apparent than real can emerge.

References: [1]Tera, F., Papanastassiou, D. A. and Wasserburg, G. J. 1974. *Earth and Planetary Science Letters.* 22:1–21. [2] Chapman, C. R., Cohen, B. A. and Grinspoon, D. H. 2007. Icarus 189:233–245 (2007). [3] Boehnke, P., Heizler, M. T., Harrison, T. M., Lovera, O. M. and Warren, P. H. 2014. Abstract #2545. 45th Lunar & Planetary Science Conference. [4] Marchi, S. et al. 2013. Nature Geoscience 6:303–307.