Summary: The evidence supporting an Early Heavy Bombardment (EHB) prior to 4.0 BY ago on the Moon suggests that it may have been more intense than the traditional Late Heavy Bombardment (LHB) at ~ 4 BY ago.

Evidence supporting an Early as well as Late Heavy Bombardment on the Moon: Evidence supporting an intense bombardment predating the traditional Late Heavy Bombardment (LHB) [1-3] includes a two-peak distribution in Overlap-Corrected Crater Retention Ages suggesting an older and younger population of basins, lower topographic relief and Bouguer gravity contrasts for the older population, and model absolute ages that suggest the Early Heavy Bombardment (EHB) occurred well before 4 BYA. These are discussed below for an inventory of lunar basins larger than 300 km diameter [4-6] based on Quasi-Circular Depressions (QCDs) in LOLA data [5,6] and Circular Thin Areas (CTAs) from model crustal thickness [7,8]. Our inventories are rated by Topographic Expression and Crustal Thickness Expression scores of each candidate on a 0-5 basis, added for a Summary Score (SS) (0-10) and considering only those with SS \geq 3 (“Full Inventory”). In the past we have compared the Full Inventory with a “Reduced Inventory” having SS > 5, but this eliminates several well-recognized lunar basins. Here we consider an intermediate “Reasonable Inventory” of 55 candidate basins with Summary Scores \geq 4.

Overlap-Corrected Crater Retention Ages: N(50) Crater Retention Ages (CRAs) for large lunar basins show two peaks, even when weaker candidates are eliminated [8] (Figure 1). The break between older and younger impact basins occurs at N(50)~65 and is pre-Nectarian [9], as others suggested based on a smaller number of basins [10]. Basins with N(50) > 65 are called “Older Population” (OP) and those with N(65) < 65 the “Younger Population” (YP).

Geophysical Contrasts. Contrasts in topographic relief and Bouguer gravity derived from profiles through the candidate basins were plotted versus Overlap-Corrected N(50) CRAs [11,12]. Preliminary results showed there is a general decrease in contrast with increasing CRA, as expected if earlier basins formed when compensation of impact topography happened more easily. These results were confirmed by a more careful analysis by two interns using more profiles for each candidate [13]. Their analysis also showed an expected diameter effect: larger basins have stronger contrasts than smaller basins of the same age.

When basins with thick mare fill (affecting topographic contrast), very small basins that do not preserve Bouguer signatures, and other anomalous cases are eliminated [12], there is a clear pattern in the contrasts (Figure 2 below): Older Population basins have topographic relief (TR) generally < 1.8 km and Bouguer gravity contrast (BC) < 350 milligals, compared with the Younger Population values of TR > 1.8 km and BC > 350 milligals. This is consistent with OP basins forming early in lunar history when the contrasts were more readily compensated.

Absolute Age Scenarios: We previously presented [11,12,14] scenarios for Model Absolute Ages (MAAs) using the few “known” absolute ages based on returned Apollo samples [15, references therein] and an Assumed Oldest Age (AOA) for the oldest inter-basin crust, several small areas of which were found to have N(50)~155. At different times we considered both AOA = 4.5 BY [14] and AOA = 4.4 BY [11] for Full, Reduced and later Reasonable Inventories [12]. Results were generally similar, but the MAAs depend greatly on the assumed age for Nectaris, which was varied from 3.9 to 4.1 and 4.2 BY. Below we consider an intermediate case of Nectaris = 4.0 BY, AOA = 4.45 BY and using the “Reasonable Inventory”. Known basin ages, Nectaris and the AOA were fit three ways (Figure 3): (a) a linear, (b) a log (x), and (c) a two branch fit where the younger branch extends a known basin-Nectaris linear fit to N(50)=65 (the trough in the CRA distribution in Figure 1) and an older branch connects this point with the AOA. In the least likely linear fit case, the older peak at ~4.1 BY (EHB) is about the same as the 3.9 BY (LHB) peak. In the more likely log(x) and two branch fits, a peak at ~4.1-4.2 BY (EHB) is stronger than the 3.9-4.0 BY (LHB) peak. This is consistent with our earlier results for “old Nectaris” scenarios [11,12,14], and strongly suggests the EHB was at least as intense and likely...
more intense than the LHB. Note this conclusion becomes even more true if the full inventory is used, because the number of “Old Population” candidate basins is even larger.

Figure 3. Upper Left: conversion from Overlap-Corrected N(50) CRAs to model Absolute Ages using ages of known basins, an assumed 4.0 BY age for Nectaris, and an Assumed Oldest Age (AOA) = 4.45 BY. Three cases are shown: a linear (purple), a log(x) (green) and a 2-branch fit (red=older branch, orange=younger branch) through the trough in the CRA distribution (red box). Upper Right, Lower Left and Right: distribution of model ages for the three cases using the same color code. Darker color is Older Population, lighter color is Younger Population. Note strength of the Early (>4.1 BY) peak compared to LHB peak (3.9-4.0) BY.

Size Frequency Distributions for both OP and YP. The evidence above strongly supports an Early as well as Late Heavy Bombardment on the Moon. In principle these could be due to two different populations of impactors. Unfortunately, the size frequency information is incomplete, especially for the Older Population (see Figure 4 below).

Figure 4. Size distribution of Old, New and Combined (Old + New) basin populations. Left: Binned diameter distributions plotted as line graphs rather than histograms (points at centers of 100 km bins). Fits through the YP (which also closely fits the OP except between 500-800 km diameters) and the combined population (excluding points in the 500-800 km range) are degree 2 polynomials. Right: cumulative frequency curves for the same populations. Note the OP falls below the YP for D<800 km and has diameter gaps down to ~500 km. This suggests a depletion or removal of basins.

Figure 4 shows size frequency information for the two populations in two ways. Both show the OP has a dearth of candidate basins in the 500-800 km diameter range compared to the YP. If the YP is fully represented in our inventory and the diameter distribution and cumulative distributions shown are representative of the impacting population during the LHB, then the EHB either had a very different size frequency distribution or what we have is incomplete. Note in the cumulative distribution the OP generally lies below the YP, strongly suggesting under-representation, and not just in the 500-800 km diameter range.

While it is possible that the size frequency distribution for the Older Population could have the unusual character of large numbers of small and large (but not middle size) objects producing mostly basin diameters < 500 km and > 800 km in size, a simpler explanation is that older basins in the middle size range (and possibly at other diameters) are missing due to the effects of later impacts that produced the LHB.

Thus it is likely the Older Population was even larger than shown in Figure 1, and the EHB peaks in Figures 3 were likely even stronger. Taken together, it appears the EHB could well have been far more intense than the LHB.

Conclusions: The distribution of N(50) Crater Retention Ages (CRAs), plots of Topographic Relief and Bouguer Gravity Contrast versus CRA, and model Absolute Ages all suggest a strong Early Heavy Bombardment (EHB) as well as the traditional Late (LHB) Heavy Bombardment on the Moon. Size frequency distributions suggest the Older Population is under-represented, likely due to the effects of the LHB. Thus the EHB may have been stronger than shown here and likely was more intense than the LHB.