LHB EVIDENCE ON ASTEROIDS.

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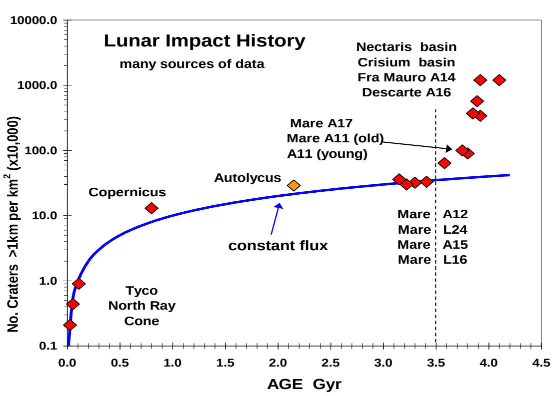
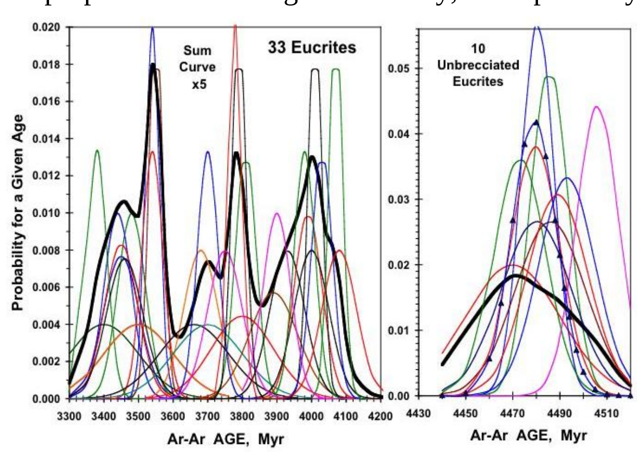
The Moon. Shortly after return and analysis of the first lunar samples, it was recognized that the lunar surface had experienced significant heating about 4 Giga-years (Gyr) ago, which produced variable to total resetting of isotopic chronometers in highland rocks. This heating was attributed to a period of large-scale impact bombardment (LHB, Late Heavy Bombardment, or cataclysm) of the Moon, long after its formation [1]. Earlier, the origin of the impacting bodies was a mystery, but presently orbital interactions of the giant planets with the Kuiper and asteroid belts is thought to be the cause. The time period over which these large impacts occurred is still poorly known. Dating of rocks thought to have derived from the large Imbrium and Serenitatis basins indicate that these formed about 3.9 Gyr ago [2]. The youngest large basin, Oriental, is thought to have formed 3.7-3.8 Gyr ago, primarily based on crater densities, not radiometric dating. Earlier, the 16th youngest basin, Nectaris, was thought to have formed ~3.9 Gyr ago, but more recent studies suggest it may be considerably older [3]. Ages of the oldest impact basins are totally unknown, although reset or partially reset ages of >4 Gyr for highland rocks are relatively common. One difficulty in using radiometric ages to determine the time period of the lunar LHB is that the Moon was extensively gardened by large impactors and the rocks experienced multiple thermal events.

Evidence of the ending time of this LHB is given by a plot of crater densities against radiometric age for various lunar features, ranging from young craters, to mare, to older impact basins (Fig. 1). Several craters, ranging over 2-2200 Myr in age, and four younger mare surfaces (Apollo 12 & 15 and Luna 16 & 24) are approximately consistent with a constant flux over the past 3.5 Gyr. Some older mare (Apollo 11 and 17) and ejecta deposits at Apollo 14, 16, and other basins indicate an older impact flux which rises well above this constant flux curve, and which may have decreased over the period 4.1-3.6 Gyr ago. These data suggest that the end of the LHB on the Moon occurred ~3.5 Gyr ago.



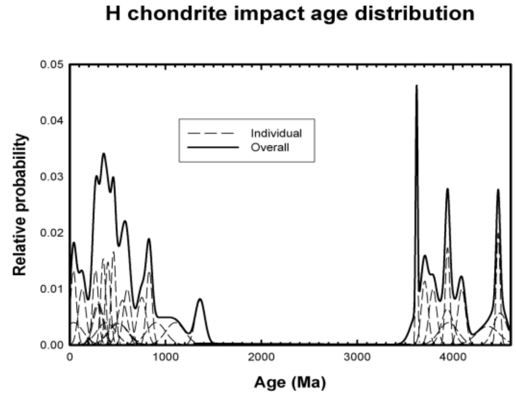
Asteroids. What about the LHB on other solar system bodies? Bogard [4] reviewed impact reset ages of meteorites and suggested that the LHB occurred on the parent bodies of HED meteorites, probably Vesta, H chondrites, and possibly IIE iron-silicate meteorites. K-Ar ages, measured by the ^{39}Ar-^{40}Ar technique, are particularly sensitive to impact resetting. No other meteorite types show obvious evidence of significant impact heating, and [4] attributed this observation to other meteorites having derived from smaller parent bodies. Hot ejecta deposits from large craters are required to reset radiometric chronometers, and such large impacts can occur only on large bodies like the Moon and Vesta, without destroying the body. Additional Ar-Ar ages of eucrites were presented by [5], and a recent review of Ar-Ar ages of meteorites and their impact history is given in [6]. Figure 2 presents a probability histogram of Ar-Ar ages from 43 different eucrites and eucritic clasts in howardites [6]. Each Ar-Ar age is represented by a Gaussian curve, where the spread of the curve is proportional to the age uncertainty; more precisely



defined ages give taller and narrower curves. The 33 curves plotted to the left represent brecciated samples, which obviously experienced impact breakage, mixing, and heating. The 10 curves to the right represent unbrecciated samples, including both basaltic and cumulate eucrites [5], which do not exhibit obvious textural evidence of impact. The heavy black lines give an average of these data. Note that the age scale is approximately continuous between the two plots.

The brecciated samples suggest impact heating events at about 4.0, 3.7-3.8, and 3.4-3.5 Gyr. By analogy with impact reset ages of lunar rocks, these likely represent large impact events on Vesta at these times. Those inferred impacts over ~3.7-4.0 Gyr fall within the range of estimated ages of some lunar impact basins. The impact(s) at ~3.5 Gyr have similar age to the end of the lunar LHB as inferred from Fig. 1. Essentially no impact ages of brecciated eucrites give ages younger than 3.4 Gyr or older than 4.1 Gyr. Apparently the age range of ~3.4-4.1 Gyr defines the period of the LHB on the Vesta asteroid.

Ages of unbrecciated eucrites plotted to the right narrowly define a single impact-heating event at 4.48 Gyr. Other radiometric chronometers suggest disturbance for some of these same meteorites [5]. This 4.48 Gyr age is younger than the formation time of eucrites measured by U-Pb, and is unlikely to represent the time of metamorphism that partially homogenized Mg and Fe in eucritic pyroxenes. Neither can uncertainty in the ^{40}K decay parameters account for this 4.48 Gyr age being slightly younger than the times of formation or metamorphism [6]. This 4.48 Gyr age was attributed to an early impact-heating event on Vesta, one apparently unrelated to the LHB [5]. Impact heating at comparable times apparently occurred on some other meteorite parent bodies [6]. Assuming these unbrecciated eucrites derived from the same parent body as the brecciated eucrites, an obvious question is how these older samples escaped impact heating during the LHB. They may have been ejected in the 4.48 Gyr event as smaller vestoids, which escaped large LHB collisions. This implies one large Vesta crater is much older than the others. Alternatively, these older meteorites may have been deeply buried on Vesta and only brought to the surface near the end of the LHB.



Some H chondrites also indicate LHB resetting of Ar-Ar ages in the same ~3.5-4.1 Gyr time period as eucrites, and minor evidence for LHB resetting exists in L and LL chondrites [4, 7]. Figure 3 (from Swindle & Kring, reference 7) gives Ar-Ar ages for H chondrites. In this figure, a few older ages may represent impact or parent body metamorphism. Many chondrite ages of <1.2 Gyr represent collisional impacts in the asteroid belt, and interestingly only chondrites seem to exhibit these young impact ages [6].

Conclusions. The LHB on the Moon also occurred on the parent body of HED meteorites, probably Vesta, and likely on the parent bodies of some chondrites. Other than possibly the IIE iron-silicate body, no other meteorite group gives obvious evidence for LHB age resetting. From meteorite data, the time of LHB resetting appears to have been confined to the period of 4.0-3.5 Gyr ago. This appears consistent with lunar data. Impactors producing large craters on Vesta would have been smaller than those producing the lunar basins, so Vesta and the Moon probably define different sizes of the LHB population.

[1] Tera, Papanastassiou, Wasserburg, *EPSL 22*, 1-21, 1974.; [2] Grange, Nemchin, Jourdan, 41st *LPSC* abstract #1275, 2010; [3] Norman, Duncan, Huard, GCA 74, 763-783, 2010; [4] Bogard, *Meteoritics 30*, 244-268, 1995; [5] Bogard &Garrison, *MAPS 38*, 669-710, 2003; [6] Bogard, *Chemie der Erde 71*, 207-226; [7] Swindle & Kring, LPI Early Solar System Bombardment Workshop, abstract #3004, 2008.