**CHRONOLOGICAL EVIDENCE FOR THE LATE HEAVY BOMBARDMENT IN ORDINARY CHONRITE METEORITES.** T. D. Swindle[1] and D. A. Kring[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721-0092 (tswindle@u.arizona.edu), [2]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058 (dkring@lpi.usra.edu).

**Introduction:** The first evidence of the Late Heavy Bombardment ("LHB"), or Lunar Cataclysm, came from Ar-Ar and Pb-Pb analyses of lunar samples [1, 2]. But was this restricted to the Moon?

In his classic review, Bogard [3] suggested that there was some evidence in Ar-Ar ages of HED meteorites, and perhaps a hint in ordinary chondrites. Meanwhile, Wasson and Wang [4], in compiling U,Th-He ages based on measured $^4$He contents and average actinide compositions for the various chemical classes, found that few chondrites had ages older than 4.0 Ga, although many had ages 3.5-4.0 Ga. In the last 10-15 years, several laboratories, including ours, have investigated a variety of shocked ordinary chondrites, as well as lunar impact glasses [5-7] and lunar meteorite impact melts [8, 9]. In addition, LHB-aged (3.5-4.1 Ga) samples of HED meteorites [10] and silicate inclusions within IIE irons [11] have also been reported.

In this abstract, we report on the growing chronological evidence for an LHB event in ordinary chondrites. As it turns out, ages between 3.5 and 4.0 Ga (LHB) are not uncommon, nor are ages >4.4 Ga (presumably from the accretionary era of the Solar System). On the other hand, ages between 2.0 and 3.5 Ga are virtually non-existent, as of yet, and ages between 4.0 and 4.4 Ga are rare, except in shocked LL chondrites, where they are common.

**"LHB" Ages of Ordinary Chondrites**: It is impossible to tell from a petrographic examination of a shocked chondrite what its age is. Hence, the chronological data base tends to grow slowly, with some events coming into focus long before others. Following is a summary of the current status of ages of ordinary chondrites, with a focus on ages older than 3 Ga.

*H Chondrites*. The impact record in H chondrites (Fig. 1) includes six meteorites with impact ages of 3600-4000 Ma [12-16], and another, Yangzhuang (melt) at 4090±40 Ma [14]. Besides three that have ages consistent with the accretionary era (4360±120, 4480±20 and >4420, respectively) [16-18], no others are >1400.

This strongly suggests that the impact history of the H chondrite parent body included, after early impacts associated with accretion, a decrease in impact flux until ~4 Ga, followed by an increase for a few hundred Ma, then a decrease. Although it has been pointed out that the near absence of pre-4.0 Ga impact ages in the lunar record could be the result of complete destruction

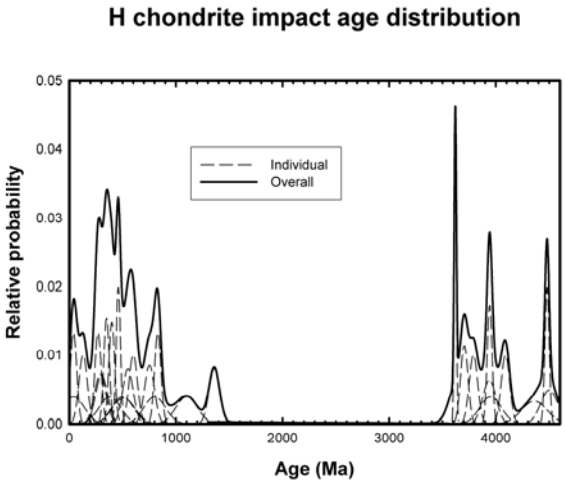


**Figure 1**: Ideogram of impact ages of H chondrites [16]. Each age is represented by a Gaussian distribution of unit area, so precisely determined ages appear as tall spikes, poorly determined ones as low, broad humps. References for ages >1.4 Ga given in text.

of impact melts during the last stages of the LHB [19],the same argument cannot be made for the H chondrites – since impact melts of ~4.5 and 3.9 Ga survived, why wouldn't those of 4.2 Ga? The much greater abundance of ages in the last ~1 Ga than in the 2 Ga before that suggests that there is a typical lifetime for melts produced in the current environment, which would mean that the number of 3.6-4.0 ages reflects a considerable increase in impacts at that time. So the lack of ages between 4.4 and 4.1 Ga, while representing a period of relative quiescence, does not necessarily represent an impact flux lower than the present, just one lower than before (during accretion) or after (during LHB) it.

*L Chondrites.* The most common shocked ordinary chondrites are shocked L chondrites. It has been recognized since the 1960s that this represents an impact event ~500 Ma ago [20]. More recently, studies of fossil meteorites in Swedish quarries [21-23], including cosmic ray exposure studies [24] and more accurate Ar-Ar dating [25], has tied the abundant shocked L chondrites to a single asteroid collision 470 Ma ago.

Ironically, although most shocked ordinary chondrites are L chondrites, the 470-Ma event is so dominant among the L chondrites that there are far fewer L

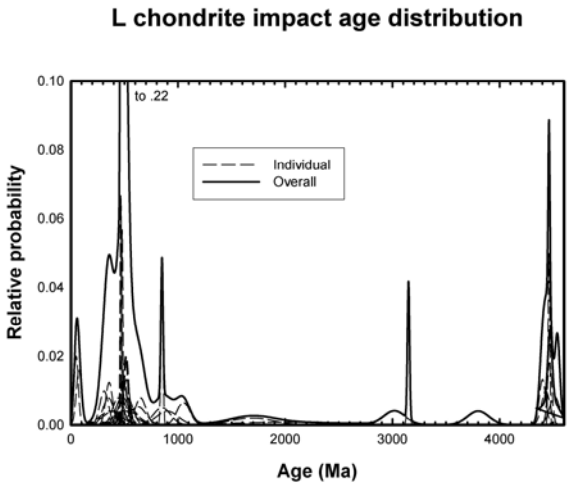


**Figure 2**: Ideogram of impact ages from L chondrites (see Fig. 1 for explanation).

chondrites with old impact ages than there are H's or LL's (Fig. 2). The total roll call of L chondrites with impact ages >1700 Ma includes two with ages of 3.0-3.2 Ga [14, 26], one with an age of ~3.8 Ga [27], and at least six with ages >4.4 Ga [28-31]. There are no ages between 4.0 and 4.4 Ga or between 1.6 Ma and 3.0 Ma.

*LL Chondrites.* The LL chondrites (Fig. 3) are dominated by ages of ~4.2-4.3 Ga [32-34], the only place where that age has been seen. Interestingly, several of those 4.2-4.3 Ga ages come from [32], who were not trying to analyze shocked meteorites, but frequently got that age anyway. There are two ~3.9 Ga ages among the 15 LL chondrite impact ages, Appley Bridge [35] and DOM 85505 [32], and two more with minimum apparent ages of 3.6-4.0 Ga, GRO 95658 and Savtschenskoje [32]. There are no others >1.3 Ga.

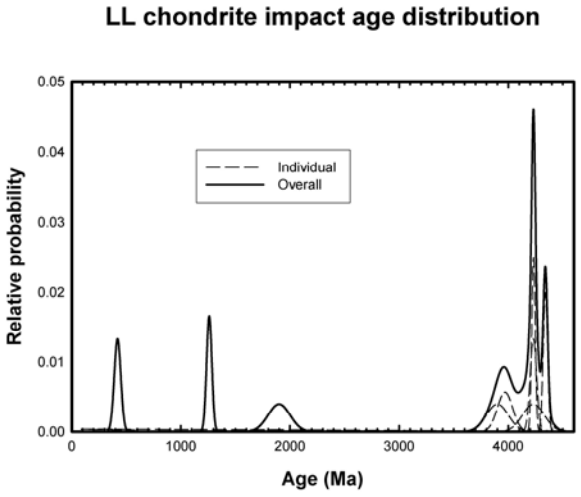


**Figure 3**: Ideogram of impact ages from L chondrites (see Fig. 1 for explanation).

**Summary:**

There is definitely an "LHB" (3.6-4.0 Ga) peak among H chondrites, and at least one meteorite in that range in both the L and LL.

There is definitely not a 3.9-4.0 Ma spike among the ordinary chondrites, although we cannot rule out the possibility of a spike becoming apparent as more data comes in.

There is a 4.2-4.3 Ma event in the LL's, not apparent in L or H, where there is a total of one meteorite (at 4.09±0.04) between 4.0 and 4.4 Ga.

"Accretionary" impacts (>=4.4 Ga) are apparent among L and H chondrites (though not LL), so impact melt can survive.

Including the long "tail" of ages later than 3.9 Ga, the ordinary chondrite data are consistent with HEDs, lunar glasses, lunar meteorite clasts, but not with Apollo melt rocks or Apollo Pb data.

**References:**

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