ASTEROIDAL CONSTRAINTS ON THE EARLY BOMBARDMENT HISTORY OF THE INNER SOLAR SYSTEM.
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Summary: Radiometric ages of meteorites from six different groups record bombardment between 4400 and 3000 Ma ago. Most ages are between 3500 Ma and 4000 Ma, and with the exception of the LL chondrites, ages between 4400 Ma and 4100 Ma are extremely rare. This is most consistent with an increase in bombardment rate and/or an increase in impact velocities at ~4100 Ma.

Introduction: Every attempt to determine the history of the flux of impactors to the inner Solar System relies on a dataset that is biased or flawed in some way. The lunar rocks we have are biased by the influence of the Imbrium Basin, which occurred near the center of the KREEP-rich region with the rocks best for dating by many techniques. We don't have enough old rocks from Mars to provide a meaningful sample, and while we have high-resolution imaging that makes it possible to determine crater densities, turning Martian crater densities into accurate ages requires a better knowledge of the relative cratering rate between Mars and the Moon than we have.

We have rocks from at least five Main Belt asteroids that have radiometric chronologies (most, but not all, determined by the ^{40}Ar-^{39}Ar technique) that appear to have been affected by impacts between ~4400 Ma and ~3000 Ma. The drawback to these is that they come from unknown (with one likely exception) asteroids with histories and/or source locations that made it possible for them to provide meteorites to Earth, but they do provide a set of dates with a different biases than the other sets we have to work with, so we will focus on them. The five sets of meteorites we will discuss are the H, L, and LL chondrites, the HED meteorites, and the silicates in IIE iron meteorites. The data used will be from two reviews [1,2] and references therein. Except where noted, we are not aware of any more recent data that change the fundamental conclusions.

It is worth comparing these to the lunar record. Early results from lunar samples were interpreted as evidence for a "terminal lunar cataclysm" a relatively short period of intense bombardment of the Moon at ~3.9 Ga. As time has passed, it has become clear that the most extreme version of this hypothesis, a period of a few tens of Ma in which all the major basins were formed and virtually all lunar impact melt rocks were formed, is an oversimplification at best. Both lunar meteorites and glass spherules collected by the Apollo program show ages extending to ages of 3.5 Ga or more recently, and evidence for impact melts at ages of 4.2 Ga or more have been found. It is clear that the impact cratering rate on the Moon was much larger between 3.5 and 4.0 Ga than it is at present, but whether that represents the tail end of a monotonically decreasing flux, a period of increased bombardment after a relative lull in cratering, or some combination (e.g., a "sawtooth" pattern) is not at all clear.

One of the clear advantages to using asteroidal meteorites is that they have definitely not been affected by Imbrium. On the other hand, the events recorded among the meteorites are largely simple crater-forming events (otherwise, the PB would have been disrupted), and are not the basin-size impact events that define the intense period of lunar bombardment. Thus, one anticipates they would produce a broader range of ages (4.1 to 3.2 Ga) vs. the lunar basins (4.1-3.8?). Clearly, smaller events would have occurred on the Moon later than 3.5 as the period basin-forming impacts waned.

Asteroidal Meteorite Data

We will discuss the data by meteorite group, where each group presumably represents a single asteroid parent body or similar bodies that accreted together in the same part of the Main Belt. Age data are displayed as relative probability plots, where each meteorite's measured age is used to construct a Gaussian curve that matches the age and standard deviation, and has the same area under it as every other meteorite. The summed value is equivalent to a histogram.

HED meteorites. Bogard [1] compiled Ar-Ar ages from 46 eucrite samples from various HED meteorites, presumably representative of the asteroid 4 Vesta. The data (Fig. 1) show a strong peak at ages >4400 Ma, a significant peak at ~3700-3800 Ma (data from nine samples overlap), and other possible peaks between 3400 Ma and 4100 Ma. There is far less evidence for any ages 4100-4400 Ma than before or after that period. Note that the old peak comes from unbrecciated eucrites, and may represent cooling or metamorphic ages, not ages of impacts. For the ordinary chondrites discussed below, the samples plotted are only those with petrographic evidence for strong shock events – there are many relatively old ages that could be shock ages, but could also be metamorphic ages.

H chondrites. The distribution for H chondrites is similar to that for eucrites, for the older meteorites. In particular, there is a cluster of ages at ages >4400 Ma, a dearth of ages between 4400 and 4100 Ma, then seven meteorites with ages of 3500-4100 Ma. There is one meteorite with an age between 4400 Ma and 4100 Ma, although it has rather large uncertainties. In addition, there are some meteorites on either side of that range whose uncertainties make them compatible with that. However, the data are most consistent with early bombardment (>4400 Ma), followed by a lull until ~4100 Ma, followed by an increase in thermal events associated with cratering. The H chondrites show a considerable amount of evidence for ages <1000 Ma, something that is largely absent in the eucrite ages, despite suggestions of relatively recent large impact events on Vesta (but see [3]).

L chondrites. The data for L chondrites is dominated by the effects of an event at 470 Ma [1,2,4,5]. Among shocked L chondrites with evidence for older ages, there are five with ages ≥4400 Ma and three with ages of 3000-3800 Ma.

Silicates in IIE irons. Silicates from five IIE irons give Ar-Ar ages of 4400 Ma or greater, but those from Watson, Kodaikanal, and Netschaëvo give concordant Ar-Ar, U-Pb and Rb-Sr ages of 3700 Ma [1].

LL chondrites. The data for LL chondrites is completely different from the other four asteroidal meteorite groups discussed. In the case of the LL chondrites, six have ages of 4100-4400 Ma, with one possible older age, and two ages of ~3900 Ma. The dominance of ages 4100-4400 Ma over those 3500-4100 Ma is what would be expected if the impactor flux was steadily declining, although more ages >4400 Ma would be likely in that scenario. On the other hand, the LL chondrites are rich in breccias, and in clast-rich and rapidly cooled impact melts, which could suggest different types of impact events or a different location within the asteroid belt for the LL-chondrite parent body [6].

Discussion: Thus, with the exception of evidence from the LL chondrite parent body, asteroidal meteorites appear to record an accretional interval of cratering events circa 4.4-4.5 Ga, followed by a lull, before the belt was dynamically excited and cratering events increased from 4.0 to 3.5 Ga.

References: [1] Bogard D. D. (2011) *Chemie der Erde, 71*, 207-226. [2] Swindle T. D. et al. (2014) *Geological Society Spec. Pub., 378*, 333-347. [3] Lindsay F. N. et al. (2015) *EPSL, 413*, 208-213. [4] Korochantseva E. V. et al. (2007) *MAPS, 42*, 113-130. [5] Weirich J. R. et al. (2012) *MAPS, 47*, 1324-1335. [6] Schmieder M. and Kring D. A. (2018) *LPS XLIX*, Abstract #1739.

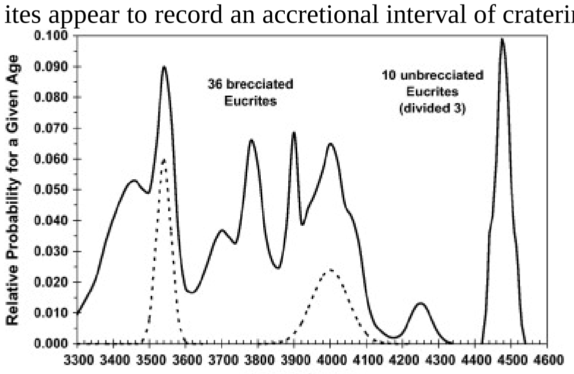

Fig. 1. Relative probability plot for 46 eucrite samples, from [1].

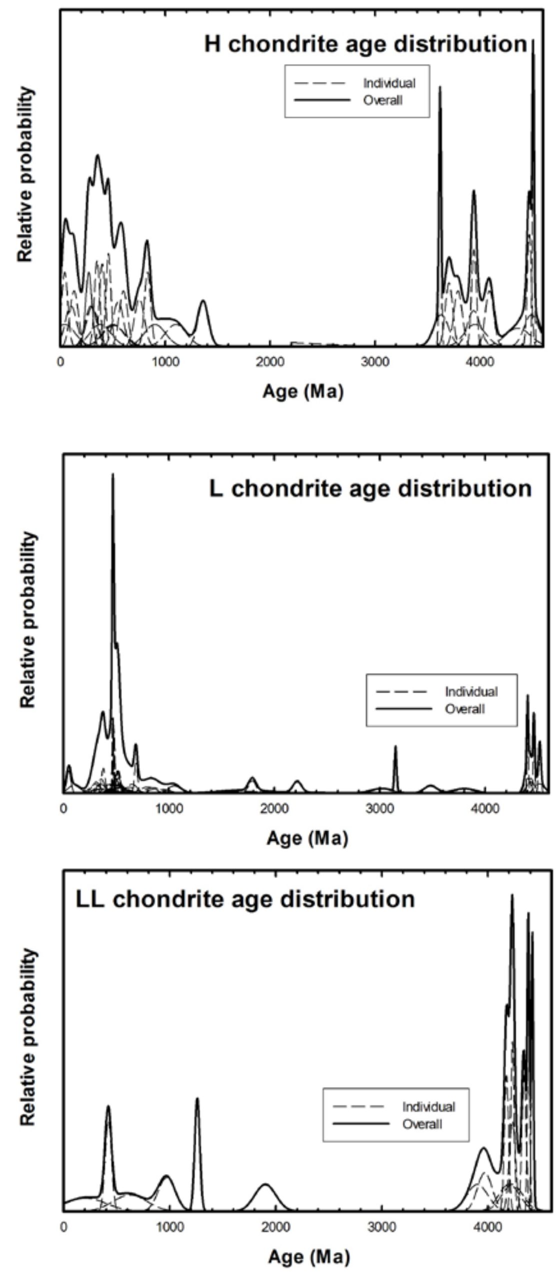

Fig. 2. Relative probability plots for ordinary chondrites that have petrographic evidence of strong shock events [2].