WAS THERE A CONCENTRATION OF LUNAR AND ASTEROIDAL IMPACTS AT ~4000 Ma? T. D. Swindle[1,2] and D. A. Kring[2,3], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721-0092, tswindle@lpl.arizona.edu, [2]NASA Solar System Exploration Research Virtual Institute, [3]Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston TX 77058.

Introduction: Ever since the first suggestion that there was a clustering in the ages of the Apollo lunar samples at ~3900 Ma [1, 2], the question of whether that clustering represented an increase in the impact flux, as suggested by [1, 2], or something else [3, 4], has been debated. Since the rate of impacts with time is a critical input parameter for dynamical models [5], as well as having a large effect of the evolution of the surfaces of planets, moons and asteroids, this is a critical question. And it is a question that is still unresolved. This abstract will not completely answer the question, but will lay out a framework for addressing the question.

Two basic approaches to the question:

Identify samples from specific events. A natural way to address the problem of the impact flux of the Moon is to identify samples from specific basins, using their chemistry or the geology of the landing site, and find the ages of the basins by finding the ages of those samples. In practice, that has generally proven difficult. The benchmark paper for this approach is the review by [6], which discusses attempts at determining the ages of the Imbrium, Serenitatis, Nectaris, and Crisium basins in this fashion (the age of the young basin Orientale can be constrained, though not precisely dated, through the ages of samples, as well). But the age of Crisium is constrained by ages of only a few Luna samples, and there is increasing doubt about the age of Nectaris (addressed later). This highlights the difficulty of interpreting the provenance of rocks within the heavily-mixed lunar regolith.

Try to interpret overall patterns of ages. Although less satisfying, this approach makes it possible to use samples that lack geological context, such as lunar meteorites, random clasts within Apollo samples that may have come from remote locations, and asteroidal meteorites (where the relationship of the impacts to the well-studied lunar basin-forming events is completely unknown). The simplest version of this approach, akin to the initial observations of [1, 2], simply looks at the distribution of ages of samples. More sophisticated approaches incorporate texture and chemical composition of lunar samples, and chemical classification (presumably identifying specific, if generally unknown, parent bodies) for asteroid meteorites. A particularly fertile set of samples for this approach has been the Apollo 16 breccias, since they may – or may not – record the crucial age of the Nectaris basin [7-9].

Two things the community seems to agree on:

There were impacts before 4000 Ma. G. Ryder argued for a cataclysmic bombardment of the Moon, based in part on his contention that no impact events older than 4000 Ma on the Moon had been definitively identified [10, 11]. However, the idea that there were no impacts before 4000 Ma has been conclusively disproven on both the Moon and among meteorites. The lunar case has recently been reviewed by [12]. In meteorites, the most prominent feature in the impact record of LL chondrites is one or more impact events at ~4200-4300 Ma [13], although there are no recorded impact events in the H or L chondrites in that time period [14]. There are also a number of impact events at >4400 Ma recorded in meteorites [14]. These could be the result of an accretional leftover population (an underlying assumption of [15]), although [16] suggested that many of them may be the result of the spread of ejecta from the Moon-forming impact on Earth.

A significant number of impacts shortly after Orientale is recorded in both lunar and asteroidal meteorites. Early papers on the Ar-Ar ages of lunar samples showed scant evidence for impact events on the Moon shortly after ~3800 Ma (e.g., [1]), but such events clearly exist. Studying the ages of recrystallized impact melt clasts from lunar meteorites, [17] argued for a cataclysmic bombardment based on the lack of ages >4000 Ma, but also showed that many of the ages were 3000-4000 Ma, not in a spike at ~3900 Ma. A similar situation obtains for meteorites. [18, 19] showed that HED meteorites experienced a bombardment (on Vesta?) that lasted until ~3400 Ma. H and L chondrites have similarly extended bombardment histories [14]. The distributions of impact ages for these groups of meteorites, while yielding more ages of ~3900 Ma than older (~4300 Ma) or younger (~3000 Ma), but also has a much broader peak that begins at ~4100 Ma, and hence seems to require an increase in impact flux earlier than the ~3900 Ma envisioned by [11].

The community doesn't seem to agree on:

The age of the Nectaris impact. Although it was originally assumed that the Apollo 16 breccias were produced by the Nectaris impact, and hence would yield the age of that event, there has been increasing doubt about whether they actually result from that basin [20, 21]. The age of Nectaris is crucial to the understanding of the Apollo 16 site. In addition, it has broader implications, since it has been suggested that the impactors from the time of Nectaris on represent a different population than pre-Nectarian impacts [22]. The difficulty in determining the age of Nectaris should also serve as a cautionary tale for attempts to determine the ages of other basins by sampling a few carefully selected sites in future exploration missions. In particularly, it is clear that it will be very difficult to attribute the age of a specific Near Side sample with a specific basin other than Imbrium, given the Imbrium overprint that is so prevalent [4]. Imbrium will not have as much of an effect on Far Side samples, but selection of the appropriate samples will still be difficult. It is likely that agreement on the ages of specific basins will only come after a sufficient number of samples have been analyzed from a variety of locations.

Whether there was a concentration of lunar and asteroidal impacts at ~4000 Ma. Given the apparent agreement that there were multiple impacts recorded on the Moon and in asteroids both before and after the original apparent spike noted by [1, 2], is there any reason to think that there was anything different about the impact cratering environment at ~4000 Ma, other than the Imbrium impact shortly thereafter? We believe there are two reasons to think there was an increase, although not the cataclysmic spike discussed by [11].

One line of evidence comes from the Moon, specifically from Apollo 16 breccias. Three studies in the past decade have looked at clasts from Apollo 16 breccias and concluded that there were multiple events between 3800 Ma and 4000 Ma that were recorded. First, [7] analyzed 25 samples, and concluded that the data fall into four clusters, depending on composition. Next, [8] analyzed multiple splits of each of six clasts, and found that while the age for any single clast was reproducible, the clasts, which had different chemical compositions, clearly had ages distinct from one another. Finally, [9] analyzed another group of >20 clasts from Apollo 16 breccias, and again found that the samples naturally cluster into different groups based on age and chemistry. All of these are inconsistent with a single resetting event (Imbrium), unless many of the samples experienced partial resetting, with the amount of resetting being virtually identical across a single clast and among clasts of similar chemical composition. While this scenario is not impossible, it is worth noting that there are cases where samples from a group of Apollo 16 breccias appear to give a range of ages, but the older-than-Imbrium ages often disagree from split to split within a clast, and there do not appear to be clusterings other than at an Imbrium age [20]. The latter case is explained well by Imbrium being the only event influencing the ages, but the others all suggest that there were multiple events recorded between 3800 Ma and 4000 Ma. It is not clear how many of them represent basin-sized events, but there is not similar evidence for that many distinct impact events in such a short time period at any other time in lunar history.

The other line of evidence comes from meteorites. As mentioned, H chondrites, L chondrites and HED meteorites all appear to have broad peaks in impact ages between ~4100 Ma and ~3400 Ma [14, 19]. It is clear that these are not a result of the Imbrium event, either directly (which is obvious) or indirectly (since they extend to times both before and after Imbrium).

Hence it appears that there is an increased impact flux at ~4000 Ma. Two recent models [15, 23], both of which are based on dynamical models but include isotopic and other constraints from the Moon and Earth, respectively, suggest that the data is best described by a “sawtooth” pattern, with an increase at 4100-4200 Ma. This provides a good explanation for the asteroidal meteorite patterns of impact ages, and also explains the extended bombardment history of the Moon seen in lunar meteorites and the multiple events in the 3800-4000 Ma timeframe seen in the Apollo 16 breccias. The lack of strong evidence for multiple events between 4000 and 4100 Ma remains puzzling, but perhaps it would be found at sites other than Apollo 16.

The “sawtooth” model [15, 23] is almost certainly a closer approximation to the history of the inner Solar System impact flux than is the “cataclysm” model of [11], just as that model was more accurate than earlier models with a continuously declining flux. However, the actual history may yet be even more complicated, as [2] suggested 40 years ago.

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