DISCORDANCY ACROSS MULTIPLE ISOTOPIC SYSTEMS IN LUNAR IMPACTITES: IMPLICATIONS FOR DATING BASIN-FORMING IMPACTS AND THE LATE HEAVY BOMBARDMENT HYPOTHESIS. B. Zhang, T. M. Harrison, A. F. Parisi, K. V. Hodges, E. A. Bell, C. M. Mercer. 1. Department of Earth, Planetary and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095, USA. 2. School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA.

Introduction: Investigations of Apollo highlands samples led to the suggestion that Moon experienced a catastrophic impact episode at ca. 3.9 Ga, termed the Late Heavy Bombardment (LHB) [1]. Tera et al. [2] found that many of these rocks yielded apparent U-Pb and Rb-Sr recrystallization ages between about 4.0 to 3.8 Ga. Several major nearside impact basins were postulated to be associated with the hypothesized cataclysm [2, 3]. If the LHB hypothesis is correct, it would have significant implications, not just for lunar history, but for our understanding of Earth habitability and early solar system dynamics [4, 5].

The LHB hypothesis, however, has long attracted skeptics [6, 7]. Hartmann [6] argued that ca. 4 Ga may have been the moment when the rate of impacts slowed to the point that evidence of older craters was no longer being obliterated by new impacts. The apparent spike in lunar $^{40}$Ar/$^{39}$Ar step-heating ages at ~3.9 Ga is equally consistent with a monotonically declining impact rate [8]. Baldwin [9] argued that the magnitude of the impact that formed the Imbrium basin was the “single overwhelming event at that time” that influenced the $^{40}$Ar/$^{39}$Ar ages of most returned Apollo rocks. Moreover, $^{40}$Ar/$^{39}$Ar data for lunar meteorites, which are the random sampling of the lunar surface, show no such spike at ca. 3.9 Ga [10].

The traditional $^{40}$Ar/$^{39}$Ar step-heating method uses small amounts of crushed sample, but all lunar impact melt rocks contain ubiquitous lithic and monomineralic clasts of sizes ranging down to tens of microns. For such samples, it is always difficult and usually impossible to isolate and date only melt components using the step-heating method, which complicates the interpretation of $^{40}$Ar/$^{39}$Ar spectra. Difficulties in reliably dating impact events are further amplified by inconsistencies between the geochronologic results obtained by applying different isotopic systems to lunar impact melt rocks. To our knowledge, none of the previously studied lunar impactites have yielded concordant dates using multiple radiometric chronometers.

In this study, we present new $^{207}$Pb/$^{206}$Pb dates for Apollo 77115,212 and 73217,83, for which ultraviolet laser ablation microprobe (UVLAMP) $^{40}$Ar/$^{39}$Ar data were presented by Mercer et al. [11]. Our primary goal in this study was to see if $^{207}$Pb/$^{206}$Pb dates for the same two thick sections studied by Mercer et al. [11] would provide corroborating evidence for the impact-melt ages they inferred from their $^{40}$Ar/$^{39}$Ar data.

Sample Descriptions: Apollo 77115,212 has a micro-poikilitic impact melt texture that contains petrographic evidence of a single melt component with some monomineralic and lithic clasts. Mercer et al. [11] presented 15 UVLAMP $^{40}$Ar/$^{39}$Ar dates of the melt, which defined an isochron indicating an apparent age of $3.834 \pm 0.020$ Ga.

Apollo 73217 may not be a simple impact melt rock. Although Huber and Warren [12] proposed that there was a single, essentially uniform granitic mesostasis in the sample, petrographic examination of 73217,83 by Mercer et al. [11] revealed evidence for the existence of three mineralogically and chemically distinctive mesostasis domains. These three domains show $^{40}$Ar/$^{39}$Ar dates peaking at $3.82 \pm 0.01$, $3.66 \pm 0.02$, and $3.27 \pm 0.03$ Ga, respectively.

Methods: In situ Pb-Pb dating was performed on a CAMECA ims1290 ion microprobe with a Hyperion-II RF ion source at UCLA. We used a ~1 nA O$_2$ primary beam with a spot size of ~5 μm under oxygen flooding. The monocollector mode was used to sequentially measure $^{204}$Pb, $^{206}$Pb, $^{207}$Pb, and $^{208}$Pb using a mass resolving power of 5400 (90% peak height). We assume that common Pb was mainly from terrestrial contamination during polishing and the local Pb isotopic composition was used for $^{204}$Pb corrections. Data were reduced by in-house software.

Results: We identified 30 phosphate crystals in the melt of 77115,212 and obtained $^{207}$Pb/$^{206}$Pb dates for 11 of them. We only used spots with $^{206}$Pb* $\geq$ 99% (N = 5), which have inverse-variance weighted mean of $3.997 \pm 0.029$ Ga (MSWD = 1.5). We present 42 $^{207}$Pb/$^{206}$Pb dates for accessory phases (Ca-phosphate, zircon, and zirconolite) in 73217,83. Analyses with $^{206}$Pb* $\geq$ 99% (N = 21) show excess scatter (MSWD = 3.0), so we multiplied the calculated uncertainty by MSWD$^{0.5}$ and calculated the weighted mean age of $3.928 \pm 0.007$ Ga. A summary of the geochronologic results is shown in Table 1.

Table 1. Summary of $^{40}$Ar/$^{39}$Ar and $^{207}$Pb/$^{206}$Pb dates for 73217,83 and 77115,212

<table>
<thead>
<tr>
<th>Sample</th>
<th>UVLAMP $^{40}$Ar/$^{39}$Ar (Ga)</th>
<th>Ion-probe $^{207}$Pb/$^{206}$Pb (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73217,83</td>
<td>3.82 ± 0.01, 3.66 ± 0.02, 3.63 ± 0.03, 3.27 ± 0.03</td>
<td>3.997 ± 0.029</td>
</tr>
<tr>
<td>77115,212</td>
<td>3.834 ± 0.02</td>
<td>3.928 ± 0.007</td>
</tr>
</tbody>
</table>
Discussion: We interpret the age of 3.997 Ga as a robust estimate for the age of the mesostasis in 71155,212. Hence, the 3.83 Ga UVLAMP date for this rock underestimates the true age of the mesostasis by over 100 Ma. Given the internal consistency of the UVLAMP data, this would imply a presumably impact-related, but not melt-forming metamorphic event at 3.83 Ga capable of completely resetting the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics of the entire sample.

For 73217,83, we consider two plausible interpretations. Interpretation 1: our $^{207}\text{Pb}/^{206}\text{Pb}$ data for 73217,83 can be reasonably interpreted as indicating a single impact melting event at $\sim$3.93 Ga, while the $^{40}\text{Ar}/^{39}\text{Ar}$ data [11] reflect variable, domain-specific resetting of Ar systematics subsequent to ca. 3.93 impact melting. Interpretation 2: there were two or more melting events from 3.93 Ga down to ca. 3.3 Ga. This would require that not all U-rich accessory minerals grew during all melting events and none of the melt-generating events recorded by the $^{40}\text{Ar}/^{39}\text{Ar}$ data caused resetting of Pb systematics in accessory minerals in the sample.

Regardless of which of the interpretations outlined above might prove correct, our new and previously published geochronologic datasets for 73217,83 and 77115,212 illustrate the complexities involved in both testing the LHB hypothesis and, more generally, dating impact events on the Moon. Although our new $^{207}\text{Pb}/^{206}\text{Pb}$ dates for 73217 are comparable to previous geochronologic results for Apollo 12, 14, 15, and 17 samples ranging between 3.92 and 3.95 Ga [13-16], it is difficult to ascribe this range unambiguously to either of the major candidates for a basin-forming impact event that might be responsible for the dated impact melts: Imbrium or Serenitatis. Moreover, the $3.997 \pm 0.029$ Ga age for the 77115,212 mesostasis is significantly older than the range commonly presumed for Imbrium and significantly younger than the newly proposed age for Serenitatis [17], which implies that the 77115 melt was unrelated to a basin-forming impact. Therefore, we suggest that U-Pb and $^{207}\text{Pb}/^{206}\text{Pb}$ dates deemed related to impact melting imply the ages of impact melt production and provide no unambiguous evidence of the age of any specific basin-forming event.

In general, most U-Pb, $^{207}\text{Pb}/^{206}\text{Pb}$, and $^{40}\text{Ar}/^{39}\text{Ar}$ datasets for lunar impact melt rocks allow for multiple interpretations with regard to the true ages of melt components. Such datasets are difficult to interpret in terms of thermal history, and convincingly relating them to the age and intensity of an impact event would require significant supplementary evidence. Nonetheless, multiple high-spatial-resolution radiometric dating systems integrated with careful petrographic and electron-probe characterizations are powerful tools to establish more reliable, complete thermal histories for lunar impacities.

Establishing a reliable, quantitative lunar impact chronology requires that all target rocks be equally amenable to producing the dateable phase. In the case of K-Ar dating, the broad presence of at least trace amounts of potassium in lunar rocks provides a somewhat level playing field. For in situ U-Pb dating, the solubilities of U-rich phases are strongly dependent on temperature, target rock composition, and the availability of the accessory phase essential structural constituent (e.g., Zr for zircon or baddeleyite). Because not every pair of target rock composition and impact condition can lead to formation of either of these phases, there could be an inherent bias implicit in using them to establish impact chronologies. That is, only melts of appropriate chemistry and thermal history will produce crystals large enough (say, $>4$ $\mu$m) for in situ chronologic investigations. For the case of a synthetic $M = 1.7$ ‘lunar granite’ [18], nearly 2000 ppm Zr would be required to saturate that melt at 1050°C. To illustrate this effect, we use the [Th] map of Jolliff et al. [19] into [Zr] by multiplying by the KREEP Zr/Th ratio of 64 [20]. Note that less than $\sim$16% of the lunar surface [19] is seemingly fertile enough to make datable Zr-bearing accessory minerals, even following extreme fractional crystallization. We caution, however, that such studies are unlikely to transcend petrothermal issues that limit the use of U-Pb or Pb-Pb dating of accessory minerals in acquiring a coherent, global lunar impact history. Thus, the LHB hypothesis, already under serious challenge, may prove untestable using current methods.