^{40}AR-^{39}AR AGES FROM IMPACT MELT CLASTS IN LUNAR METEORITES DHOFAR 025 AND DHOFAR 026 B. A. Cohen[1,3], T. D. Swindle[2], L. A. Taylor[3], and M. A. Nazarov[4], [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i, Honolulu HI 96822 (bcohen@higp.hawaii.edu); [2]Dept. of Planetary Sciences, The University of Arizona, Tucson AZ 85721; [3]Planetary Geosciences Institute, University of Tennessee, Knoxville TN 37996; [4]Vernadsky Institute of Geochemistry, Moscow 117975, Russia.

Introduction: The lunar meteorites are a growing and extremely valuable sample set. The stochastic nature of lunar impact launches and high Al_2O_3 content of the lunar highlands meteorites implies that at least some of the lunar meteorites are derived from the lunar farside, the only samples we have of an entire hemisphere of the Moon. Theories of lunar evolution based on the Apollo and Luna rocks are especially ripe for reexamination in light of this new sample set.

The proposed "terminal lunar cataclysm," where a spike of impactors hit the Earth-Moon system at about 3.9 Ga [1, 2], is based in large part on the fact that no lunar impact melt samples from the Apollo or Luna collections have ages older than about 3.85 Ga [e.g., 1-5]. However, these samples were probably affected by the nearside basin-forming impacts. Lunar meteorites represent a more random sampling of the lunar surface and dating of lunar meteoritic impact melts is a good test of the lunar cataclysm hypothesis [6].

Previous work on the highland lunar meteorites MAC88105, QUE93069, DaG262, and DaG400 found impact melt samples from at least 7 different impact events on the Moon, all of them at or more recent than 3.9 Ga [7]. This work provides ^{40}Ar-^{39}Ar ages of impact melt samples from two unpaired lunar highland breccia meteorites, Dhofar 025 and Dhofar 026. Nine impact melt clasts within Dhofar 025 have ages between 500 Ma and 4.0 Ga. One sample provides a crystallization age for crystalline impact melt breccia Dhofar 026 of ~ 500 Ma.

Samples: Lunar meteorite Dhofar 025 is a highlands regolith breccia with little to no basaltic component [8, 9]. Approximately 75% of the clasts are crystalline impact melts; the largest have coarse- (10 µm) to fine-grained (<1 µm) microporphyritic textures. Dhofar 026 is a clast-poor, anorthositic, crystalline melt breccia [8, 10, 11]. Solar wind abundance measurements show that the two meteorites are unpaired [12]. The bulk composition of large (>200 mm), uniform, crystalline, clast-free impact melt clasts in Dhofar 025 were determined using defocused-beam analyses. The bulk composition of Dhofar 026 is taken as an approximation of the impact melt composition, though the two samples were taken from the groundmass with pains to avoid entrained clasts and gabbroic material. The dissimilarity of Dhofar 025 and Dhofar 026 impact melts to Apollo impact melts makes them excellent candidates for age dating in order to further constrain lunar bombardment history.

80-µm thick sections were made from each meteorite. A microcoring device (diamond-bit drill attached to a rotating microscope stage) was used to extract individual impact melt clasts from the thick section. The weights of the resulting samples are listed in Table 1. Samples were irradiated in position L-67 of the Phoenix Ford Reactor at the University of Michigan for 575 hours, producing a J-factor of 8.55×10^{-2}. K_2SO_4 and CaF_2 salts were irradiated simultaneously to correct for reactor-induced interferences, and MMhb-1 hornblende was used to derive the neutron fluence.

Laser step-heat experiments were carried out in the University of Arizona noble gas lab with a continuous Ar-ion laser heating system. Heating steps were determined first by passing a 10A (minimum possible) beam through a polarizer and then by increasing the amperage in steps no smaller than 0.5A each. The absolute temperature for each step is unknown. However, this information is not critical to our interpretations.

In addition to blank and interference corrections, argon produced by chlorine in the extraction system and cosmic ray spallation on the lunar surface were subtracted from each sample. Using system blanks, the contribution to mass 36 by ^{35}Cl was ~10% and to mass 38 by ^{37}Cl was ~15% (or ~5% of the ^{35}Cl measured since $^{37}Cl/^{35}Cl$ =0.32). Cosmogenic argon was determined by deconvolving the relative contributions of ^{36}Ar from spallation ($^{38}Ar/^{36}Ar$=1.5) and from atmospheric and/or lunar argon ($^{38}Ar/^{36}Ar$=0.19). These corrections completely subtracted both ^{38}Ar and ^{36}Ar from all samples, but were only minor correction to ^{40}Ar. System blanks varied by 25% at most over the data collection period (3 weeks).

Results: Our data are summarized in Table 1. Due to the small size and low K content (150 to 900 ppm), very few heating steps could be performed on each sample. Because anomalously high ages (attributed to outgassing of air from residual epoxy) were seen in previous samples [7], we used a polarizer to achieve several lower-temperature heating steps for each sample. In most samples, however, the first ~25% of ^{39}Ar release yields ages older than the solar system. This should be kept in mind in the total fusion cases. The true age is likely younger than the total fusion age owing to these anomalously old first heating steps.

Fig. 1a is an ideogram of the sample ages. The ideogram is a histogram that takes into account uncertainty in each determination [7]. The clasts in Dhofar 025 span a wide range of ages, from 0.56 to 4.1 Ga. The 3 oldest samples have large uncertainties associated with them; one is a total-fusion age, another has a younger age using the isochron diagram. The meaning of the cluster age ~4.1 Ga is therefore ambiguous at best. Groups of 2 samples each cluster at 3.1 Ga and

565 Ma. Individual samples 25G and 25P do not overlap other samples within their 1σ uncertainties.

Samples 26C and 26D are the only samples run from Dhofar 026. Sample 26D did not yield an age, but 26C has a well-defined age of 569 ± 11 Ma.

Conclusions: It is reasonably clear that there are at least three distinct impact events recorded in Dhofar 025 clasts, one relatively old (~4.0 Ga), one slightly younger (3.1 Ga) and one of Copernican age (~500 Ma). If samples 25G and 25P represent distinct events, as many as 5 impact events could be recorded in this meteorite (Fig. 1b). The 500 Ma event recorded by Dhofar 026 is its crystallization from an impact event that may or may not be the same event recorded in the young Dhofar 025 samples. Even if Dhofar 026's distinctive multicrystalline texture is the result of devitrification, the impact age should not be significantly affected.

It is interesting that, despite the solar wind abundance differences between the two meteorites, clasts of the same age turn up in both meteorites. In fact, clast 25T is a feldspathic, poikilitic impact melt that, in thin section, looks similar to the Dhofar 026 groundmass. Coupled with the fact that a 500 Ma impact event must be relatively small (<100 km) and create only local impact melt, this suggests that Dhofar 025 may have been assembled from regolith near the Dhofar 026 impact site, though the assembly age for Dhofar 025 must be younger then the clasts within it.

Table 1: Samples and best fit ages

Sample	Weight (μg)	% ^{39}Ar in plateau	Age (Ga) [1]
25 B	13	85	3.145 ± 0.200 *2.864*
25 D	18	82	4.012 ± 0.199 *3.952 ± 0.282*
25 G	17	28 [2]	3.745 ± 0.312
25 H	29	64	2.924 ± 0.831
25 K	22	38	4.198 ± 1.920
25 P	48	80	2.694 ± 0.443
25 Q	43	100 [2,3]	0.574 ± 0.087
25 S	22	100 [2,3]	4.156 ± 0.149
25 T	4	100	0.564 ± 0.025
26 C	17	100	0.569 ± 0.011
26 D	7	—	—

[1] Plateau age, *isochron age*
[2] Plateau consists of single heating step
[3] Total fusion ages are likely older than the true age

A number of factors may work to increase the apparent age of impact melt samples, including incompletely melted clasts, rapid cooling, and epoxy degassing. Even taking these effects into account, we have still not found evidence of impact melt older than ~3.9 Ga within error, as would be expected in a smooth-decline bombardment scenario.

Interestingly, the presence of 500 Ma impact melt in both Dhofar 025 and 026, and young impact melt ages in other lunar meteorites [7], contrasts with the relative paucity of Copernican-aged samples in the Apollo and Luna collections. It may be that recent, local impact melt dominates the very surface of the lunar regolith, thus to be readily incorporated into regolith meteorites [13].

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Figure 1: a) Ideogram of impact melt ages and b) histogram of impact events in Dhofar 025 and 026