ONLY SPECIFIC LUNAR IMPACT GLASSES RECORD EPISODIC EVENTS ON THE MOON. N. E. B. Zellner[1], P. Q. Nguyen[2], O. Vesa[1], R. D. Cook[1], S. T. Blachut[1], J. W. Delano[3], T. D. Swindle[4], S. Beard[4], and C. Isachsen[4], [1]Department of Physics, Albion College, Albion, MI USA 49224, [2]Department of Physics and Astronomy, Michigan State University, East Lansing, MI USA 48823 [3]Department of Atmospheric and Environmental Science, University at Albany, Albany, NY 12222, [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ USA 85721.

Introduction: Energetic impact events on the Moon's surface generate droplets of melt that are cooled during ballistic transport and subsequently deposited in the surrounding regolith. These impact glasses retain the chemical signature of the source material (especially refractory element ratios) from which they were derived, and in combination with $^{40}Ar/^{39}Ar$ age data, provide a wealth of valuable information for interpreting the impact history of the Moon [e.g., 1].

An accurate understanding of lunar impact flux can also help address the Earth's own impact flux. In this study, compositional data and $^{40}Ar/^{39}Ar$ ages for impact glasses collected at the Apollo 14, 16, and 17 sites are presented and re-interpreted. The implications for the Moon's impact flux are discussed.

Methods: We have revisited the compositional and $^{40}Ar/^{39}Ar$ age data for ~100 glass samples that had been previously characterized [1-4] in order to refine previous interpretations of the lunar impact flux. To this data set, we have added 23 new impact glass compositions and $^{40}Ar/^{39}Ar$ ages (Table 1). These glasses were analyzed by electron microprobe and via the laser step heating technique in conjunction with an argon mass spectrometer [as described in 1-4].

Age data for impact glasses were assessed as "good", "fair", or "poor", depending on how much ^{39}Ar was released and in how many concordant steps [1]. In order to approximate the relative size of the impact (i.e., large enough to have transported material from a distant site or relatively small such that only local regolith was affected), compositions of local regolith from each site were included for comparison to the compositions of the impact glasses. Glass compositions were then broadly characterized as "exotic" or "local" [e.g., 2]. Glasses with similar ages and similar compositions were ascribed to a single impact event, while glasses with similar ages and different compositions were ascribed to multiple impact events occurring in the same time period at different locations.

Discussion: In each of the Apollo regolith samples studied (14259, 64501, 66041, 71501), glasses of both "exotic" and "local" composition were found. Additionally, a large fraction of the glasses with local compositions were spherical in shape, while glasses with exotic compositions were not, following the findings of [2]. Figure 1 shows the compositions and shapes of several impact glasses from Apollo 14 regolith sample 14259 compared to the Apollo 14 regolith [9-11].

Furthermore, the glass size and composition were evaluated against the quality of its $^{40}Ar/^{39}Ar$ age. Glasses with sizes ≤200 μm and lowest Ar-retentivity as indicated by their low X(NBO) (i.e., non-bridging oxygens; [1, 5, 6]) were most commonly found to yield $^{40}Ar/^{39}Ar$ ages with the highest uncertainties and the lowest-quality age plot (i.e., "fair" or "poor"), though there are some exceptions (Table 1).

>3500-Ma Glasses: After applying selection criteria (above) to both previously analyzed impact glasses and newly analyzed impact glasses, 11 glass shards collected at three different landing sites show "good" ages >3500 Ma, coincident in time with the tail end of the late heavy bombardment (Figure 2). While some possess the same composition as the regolith in which they were found (i.e., "local"), others possess a composition different from the regolith in which they were found (i.e., "exotic"). These characteristics of similar ages and multiple compositions indicate that they represent multiple large and small impacts during this time. Interestingly, two of these glasses were collected at different landing sites yet have a strikingly similar composition and age (red circle in Figure 2). In general, these impact glasses support the sawtooth view [e.g., 7] for the "shape" of the late heavy bombardment.

Young Glasses: Though small in number in the data reported herein, glasses with $^{40}Ar/^{39}Ar$ ages less than ~1000 Ma are usually spherical. This is consistent with previous findings [1].

Conclusion: Glasses with compositions exotic to the local regolith can constitute a large fraction of material at a given site and are usually non-spherical in shape. These glasses most likely originated in impact events distant from the collection sites of the Apollo samples. Glasses with $^{40}Ar/^{39}Ar$ ages >3500 Ma were generated by impacts at the end of the late heavy bombardment. Since spherical impact glasses are commonly young (i.e., <1000 Ma), studies that select spherical impact glasses [e.g., 8] are intrinsically biased toward young ages. An understanding of the Moon's impact history and the amount of delivered organic material to the early Earth requires accounting for the age, shape, and composition of impact glasses.

References: [1] Zellner N. E. B. and Delano J. W. (2015) *GCA*, **161**, 203-218. [2] Delano J. W. et al. (2007) *MAPS*, **42**, 993-1004. [3] Zellner N. E. B. et al. (2009) *MAPS*, **44**, 839-852 [4] Zellner N. E. B. et al. (2009) *GCA*, **73**, 4590-4597. [5] Mysen B. O. and Richet P. (2005) Silicate Glasses and Melts: Properties and Structure. Elsevier, Amsterdam. 560pp. [6] Lee S. K. (2011) *PNAS*, **108**, 6847-6852. [7] Morbidelli A. et al. (2012) *EPSL*, **355-356**, 144-151. [8] Culler T. S. et al. (2000) *Science*, **287**, 1785-1788. [9] Laul J.C. et al. (1982) *JGR* **87**, A247-259. [10] Papike J.J. et al. (1982) *Rev. Geophys. Space Phys*. **20**, 761-826. [11] Rose H.J. et al. (1972) 3rd LSC 1215-1229..

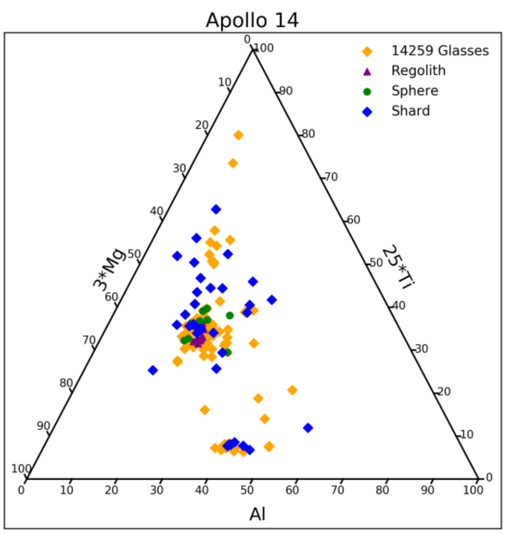

Figure 1. Apollo 14 impact glasses, identified by shape and compared to local regolith [9-11].

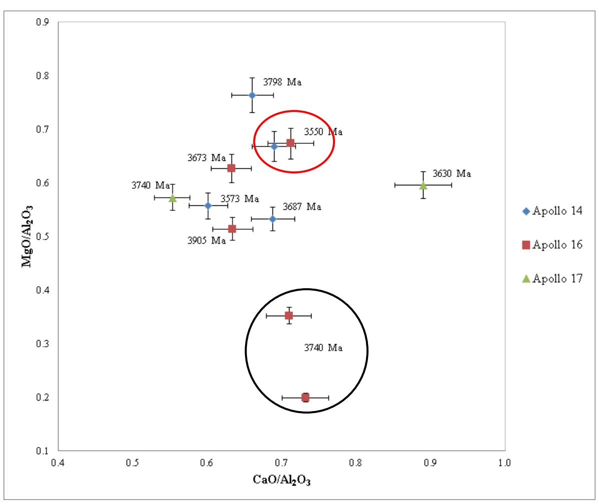

Figure 2. Lunar impact glasses from three landing sites that have $^{40}Ar/^{39}Ar$ ages >3500 Ma. Error bars are 4.25%. The red circle encompasses impact glasses that possess similar compositions and ages but were collected at two Apollo landing sites. The blue circle shows glasses from [2].

Table 1. Age and compositional data for 23 newly analzyed lunar impact glasses from the Apollo 14, 16, and 17 landing sites. Quality (Q) of age data is presented as good (g), fair (f), or poor (p). "ND" indicates age and/or uncertainty was not determined. Two glasses with ages >3500 Ma are shown in Figure 2.

Site ID	Age ±2σ Unc. (Ma)	Size (μm) Shape	Mg/ Al_2O_3	CaO/ Al_2O_3	X(NBO)	Q
A14 8	825 ±126	174 shard	0.38	0.60	0.30	f
A14 11	1310 ±20	300 shard	0.67	0.66	0.32	g
A14 16	3557 ±249	300 shard	0.67	0.69	0.32	g
A14 21	213 ±85	251 oblong	0.67	0.61	0.32	g
A14 25	326 ±86	200 dumbbell	0.54	0.62	0.28	f
A14 26	1792 ±68	300 shard	0.67	0.69	0.33	g
A14 29	1088 ±87	251 sphere	0.69	0.62	0.31	f
A14 43	491 ±63	251 shard	0.84	0.94	0.42	g
A14 65	3798 ±226	200 shard	0.76	0.66	0.34	f
A14 117	287 ±213	200 sphere	0.57	0.62	0.30	p
A14 123	3000 ND	200 sphere	0.57	0.62	0.29	p
A14 145	3000 ND	150 sphere	0.51	0.64	0.28	p
A14 148	363 ±122	251 sphere	0.59	0.65	0.30	f
A14 163	3135 ±611	200 shard	0.58	0.66	0.30	f
A14 167	106 ±19	300 shard	0.55	0.61	0.28	g
A14 172	ND	276 shard	0.63	0.66	0.31	p
A14 177	4172 ±791	300 shard	1.47	1.01	0.50	p
A16 191	1000 ±230	251 shard	0.68	0.65	0.32	f
A16 204	3905 ±168	350 shard	0.51	0.63	0.24	g
A16 207	925 ±358	300 shard	0.66	0.78	0.36	f
A16 231	1573 ±190	324 shard	0.67	0.76	0.28	g
A16 262	2818 ±249	200 shard	0.56	0.65	0.28	f
A16 509	ND	150 shard	0.90	0.90	0.45	p