Impacts in the Earth-Moon System as Told by Lunar Impact Glasses

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Introduction: Impact events have played important roles in the evolution of planets and small bodies in the Solar System. Over 500 impact glasses from four Apollo regolith samples have been geochemically analyzed and a subset has been dated by the $^{40}Ar/^{39}Ar$ method.

These 65 dated glasses show interesting trends in the bombardment history in the Earth-Moon system that do not necessarily correlate with the history shown by lunar meteorites and other lunar samples individually. Using Apollo 14 glass spherules, [1] argued that over the past ~3.5 Ga, the cratering rate decreased by a factor of 2-3, while [2] found that impact melt clasts show no ages more than 1σ older than 4.0 Ga. Similarly, the work of [3] showed that very few Apollo 12 impact glass spherules have old (>3200 Ma) ages. The ages of our impact glasses, which are comprised of spherules and fragments, from wide-ranging Apollo landing sites, are as old as ~4000 Ma and represent multiple old impact events into geochemically similar and different terrains. Understanding all of these samples together provides important information about the geology of the impacted body and the age of the impacting episodes. Specifically, impact glasses provide another set of data to address the question of whether or not there was a lunar cataclysm and to shed light on its details if it did happen.

Lunar Impact Glasses: Lunar impact glasses possess the refractory element ratios of the original fused target materials at the site of impact [4] and offer the potential for providing information about local and regional units and terrains. Orbital data [e.g. 5] has been used to show that impact glass composition(s) most often represent regolith composition(s), and old ages represented in our impact glasses and in some of the glasses of [1] show that old glasses are not necessarily destroyed. The compositions of lunar impact glasses indicate their original geology, often several hundreds of kilometers away from the site where they were collected by the Apollo astronauts [e.g. 6]. In this way, "exotic" and "local" regolith compostions can be determined [5, 6] in an effort to distinguish among impact events.

Sample Analysis: Glasses from Apollo 14 regolith 14259,624, Apollo 16 regoliths 64501,225 and 66041,127, and Apollo 17 regolith 71501,262 were analyzed for Si, Ti, Al, Cr, Fe, Mn, Mg, Ca, Na, and K using a JEOL 733 electron microprobe in the Department of Earth and Environmental Sciences at Rensselaer in the manner described by [5]. Uncertainties in the measurements were usually < 3% of the amount present. These compositions can be seen in Figure 1.

Impact glasses were subsequently irradiated and analyzed in order to determine their $^{40}Ar/^{39}Ar$ ages. Laser step-heating on these samples was carried out in the University of Arizona noble gas lab, in the manner described by [6]. Finally, several spherules of Apollo 15 volcanic green glass, which has a well-defined ^{40}Ar-^{39}Ar age, were used as isotopic working standards in order to verify that the data reduction procedure resulted in expected ages within uncertainties.

Results: Lunar impact glasses show ages that range from ~20 Ma to ~4000 Ma, spanning most of lunar history (Figure 2). Uncertainties in these ages depend on the amount of K in the sample and the amount of Ar detected by the mass spectrometer, but when considering geochemistry together with chronology, certain events become distinct. For example, [6] showed that at a 2σ level, four glasses represent one distinct impact event at ~3730 Ma into the same compositional terrain most similar to the basaltic andesitic (BA) glasses found by [7]. This integrated approach thus rules out that these four impact glasses were formed during four separate events. Similarly, a suite of 12 impact glasses from the Apollo 14, 16, and 17 regoliths shows formation ages of ~800 Ma [8], as seen in Apollo 12 samples [3, 9], all with different geochemical compositions, implying some sort of global lunar impact event that has not yet been seen in most meteorites or in terrestrial samples.

Finally, of the samples analysed so far, there is no indication of an increase in recent impact events, as reported by [1, 3] and modeled by [10], nor is there evidence of impacts on the Moon during the time interval of 400 – 500 Ma ago, when the meteorites record the break-up of the L chondrite parent body in the Asteroid Belt [11]. Perhaps debris did not hit the Moon; perhaps this is solely an artifact of sampling.

From Figure 2, it can be seen that, ages >4000 Ma are rare or absent, as is true for Apollo impact rocks [11], impact melts from lunar meteorites [2], and other lunar impact glass data sets [1,3]. However, like the lunar meteorite impact melts and ordinary chondrites, but unlike the Apollo samples, ages ~3500-4000 Ma are common in our data set. These ages are not evident in the Apollo 12 impact glasses, which [3] attributes to the soil sample having come from the bottom of an ejecta deposit of recently inverted stratigraphy, and the trend is hard to determine in [1]. While the histogram in [1] does show spikes in this time interval, the data set may unfortunately be confounded by the possibility of volcanic glasses composing a significant fraction of the “impacts”, as described in [6].

Conclusions: When age data from all lunar samples are analyzed collectively, we can begin to understand when impact events occurred and how widespread they were. Specifically, by integrating geochemistry and age [6], multiple impact samples formed at the same time in the same terrain can be eliminated from the data set. The challenge comes in trying to distinguish among the impact events, including determining which samples (impact glasses, melt rock, meteorites) were formed during the same impact event and which were not, so that the impact flux is not artificially inflated.

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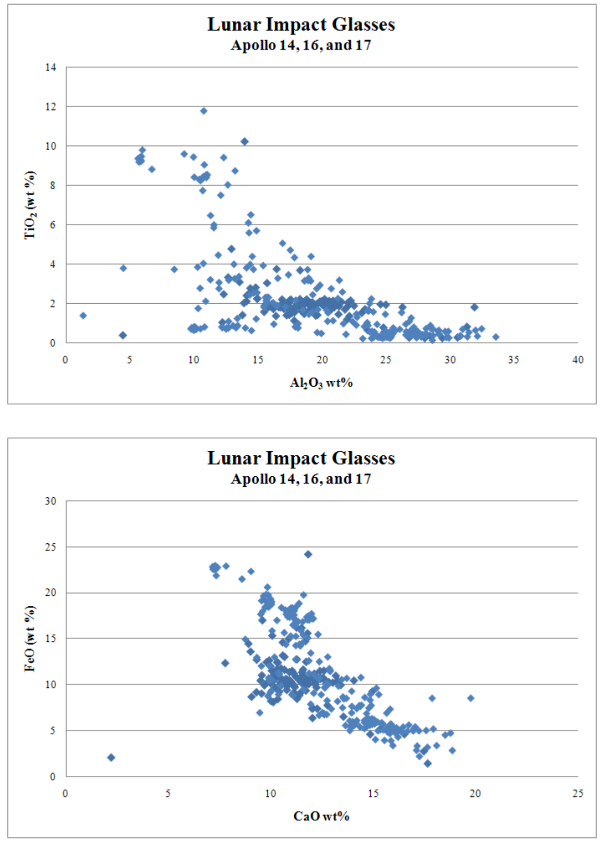

Figure 1. Compositions of over 500 lunar impact glasses.

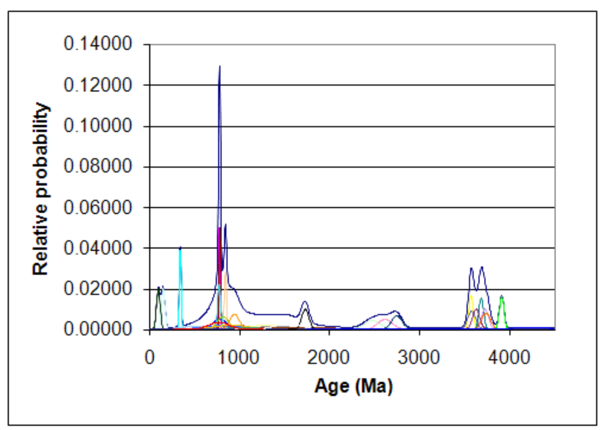

Figure 2. Ideogram of ages from 35 lunar impact glasses whose ages have so far been determined, with 2σ uncertainty. An ideogram of the entire data set will be presented at the workshop. The event described in [6] at ~3730 Ma is shown as one event and not four.