Lunar Glass Sampling by the Artemis Crew: Big Science from Small Samples N. E. B. Zellner Department of Physics, Albion College, Albion, MI USA 49224 (nzellner@albion.edu).

Introduction

Lunar impact and volcanic glasses are small samples that can resolve big science questions about the timing of the lunar impact flux in particular and the Moon's evolution in general. They can also provide important information about areas of the Moon not sampled by Apollo or Luna missions or lunar meteorites [e.g., 1]. Much of the 382 kg of material returned from the Moon by the Apollo astronauts consists of lunar regolith, and glasses are abundant [e.g., 2]. However, their provenances of origin are not usually well-constrained. Targeted sampling of glasses with particular compositions, in the context of local and regional geological information, would elucidate answers about the Moon's history. Investigations of these samples would further support using the Moon as a "mini planet" for understanding planet formation in our Solar System and planetary systems around other stars [e.g., 3]. The compositions of these glasses can be easily measured with hand or other instruments by the human crew.

Potential Science Investigations

Impact Glasses: Formed in melted impact ejecta during ballistic flight, lunar impact glasses were an unexpected find in the Apollo samples. Detailed geochemical and chronology investigations in the past decade have shown that lunar impact glasses reveal interesting trends in the impact flux in the Earth-Moon system [e.g., 4, 5; Figure 2], some of which appear to coincide with significant terrestrial events [e.g., Ordovician extinction at 480 million years ago (Ma), 6; global melting of Snowball Earths at 660-710 Ma and 645-655 Ma, 7]. Simple measurements of refractory elements [8] and element ratios [e.g., 9] allow impact glasses to be easily distinguished from volcanic glasses, and *in situ* measurements will ensure that glasses could be easily identified.

Volcanic Glasses: Volcanic glasses formed during fire-fountaining events when the Moon was geologically active. Sampling of these glasses would lead to a better understanding of the lunar dynamo [e.g., 10, among others] and the source of the Moon's volatile-rich material, including water [e.g., 11]. Furthermore, detailed investigations of these glasses could also reveal information about depth of glass origin [e.g., 12], advancing our understanding of the evolution of small bodies.

***Regolith Transport*:** Impact processing of the lunar surface is not well-constrained, and the current flux of meter- and smaller scale impacting objects has been measured to be significantly higher than predicted by the standard production and chronology functions [e.g., 13, 14]. Identifying and sampling glasses – whether volcanic or impact – can reveal important information about the compositions of regolith materials, both at depth and at sites distant from the Artemis landing and science investigation sites. Identification of impact glasses, in concert with high-resolution orbital data, may allow the source craters to be revealed. In general, these studies would improve our understanding of the mechanics that govern regolith transport processes.

Solar Wind: The nature of the solar wind can be investigated using glasses, too. For example, isotopes of argon in samples collected by the Artemis crew can be measured in Earth-based laboratories and may provide evidence for changes (if any) in the solar wind composition over time. Samples collected from depth or from areas protected by the Earth's magnetotail would be especially useful.

Resource Utilization: Over 25 different compositional groups of volcanic glasses have been identified [e.g., 15] indicating multiple different reservoirs of material. Importantly, high concentrations of Mg, Ti, Fe, and S have been measured in the volcanic glasses found in the Apollo regoliths, all of which could be extracted and used during future robotic and human landing missions to the Moon [e.g., 16, 17, 18; among others]. On a small scale, gas in vesicles in volcanic glasses could be extracted [19] for use by humans or robots. On a large scale, dark mantle deposits of high-Ti pyroclastic material (e.g., as seen at Sinus Aestuum) could be used for shielding habitat modules [e.g., 20,21], and old high-Ti regoliths would be promising areas of He^3 enrichment [22]. The glasses could also be potential sources for ceramics and fiberglass [23].

Examples of Recent Studies

As analytical instruments and techniques have improved, geochemical studies of lunar glasses have become more focused.

Formation Ages: Argon mass spectrometers capable of analysing small glasses with even smaller amounts of argon have become available. Ages derived from U-Pb and "chemical" U-Th-Pb [e.g., 24,25] have also been assigned to impact and volcanic glass spherules, though in general, these ages do not agree with measured ^{40}Ar/^{39}Ar ages [26].

Impact Flux: While most volcanic glasses are spherical, impact glasses come in a variety of shapes, including spherules and shards (i.e., fragments). Careful investigations tell different stories, however. For example, Zellner and Delano [4] observed that impact spherules are more likely to be young and thus reflect recent impact events, while shards reflect impact events over the age of the Moon. Using results from a model of impact flux scenarios, Huang *et al.* [27] suggest that the excess of young ages for lunar impact glass spherules is likely due to limitations of the sampling strategy undertaken by the Apollo astronauts and does not reflect an actual increase in the recent lunar impact rate.

Lunar Magnetism: Volcanic glasses can acquire and retain a permanent magnetic remanence generated by the lunar dynamo. Recent advances in instruments capable of measuring magnetic fields in small glasses now allow those investigations to proceed [e.g., 29].

Careful planning and sampling of glasses conducted by the Artemis crew, along with geochemical and chronology investigations of these samples in Earth-based laboratories, would help to resolve discrepancies, address current high-priority questions, and even present science questions we do not yet know to ask.

Relevance to Artemis Science Goals

The science investigations listed herein would address portions of objectives listed in the Lunar Exploration Roadmap (version 1.3, 2016), including Objective Sci-A-7, to understand the impact process; Objective Sci-A-8, to determine the stratigraphy, structure, and geological history of the Moon; Objective Sci-B-1, to understand the impact history of the inner Solar System as recorded on the Moon; and Objective FF-C-10, to develop the capability to acquire and use local resources to sustain long-term exploration crews (LER, 2016). Understanding the depth and distribution of volcanic (pyroclastic) glasses would address portions of Strategic Knowledge Gap Theme 1 (Understanding the Lunar Resource Potential), Category 1-E: Composition/volume/distribution/form of pyroclastic or dark mantle deposits and characteristics of associated volatiles (page 19; LEAG, 2016). Furthermore, these investigations would support aspects of NASA's Strategic Goal #2, to extend human presence to the Moon and allow for sustained operations on the lunar surface (page 19; NSP, 2018), as well as several of the goals in the Artemis Science Plan [e.g., 3].

References: [1] Zellner N. E. B. (2019) *JGR*, **124**, 2686-2702. [2] Reid A. *et al*. (1972) *Proc. 3rd Lun. Sci. Conf.*, 363-378. [3] Bussey B. (2020) Artemis Science Plan. [4] Zellner N. E. B. and Delano J. W. (2015) *GCA*, **161**, 203-218. [5] Zellner N. E. B. (2017) *OLEB*, **47**(3), 261-280. [6] Schmitz B. *et al*. (2003) *Science*, **300**, 961-964. [7] Koeberl C. and Ivanov B. A. (2019) *MAPS*, 1-13. [8] Delano J. W. (1991) *GCA*, **55**, 3019-3029. [9] Delano J.W. *et al*. (1981) *Proc. Lun. Plan. Sci.*, 12B, 339-370. [10] Weiss B. P. and Tikoo S. M. (2014) *Science*, **346**, 1246753. [11] Saal A. E. *et al*. (2008) *Nature Letters*, **454**, 192-196. [12] Delano J. W. and Ringwood A. E. (1979) *Proc.10th Lun. Plan. Sci. Conf*., 286-288. [13] Oberst J. *et al.* (2012) *Planet. Space Sci.* **74**, 179–193. [14] Speyerer E. J. *et al.* (2016) *Nature*, **538**, 215-218. [15] Delano J.W. (1986) *JGR*, **91**, D201–D213. [16] Vaniman D. T. and Heiken G. H. (1989) in *Workshop on Lunar Volcanic Glasses: Scientific and Resource Potential*, eds. J. W. Delano and G. H. Heiken, LPI Technical Report #90-02. [17] Taylor L. A. and Carrier W. D. (1993) *Resources of Near Earth Space*, eds. J. Lewis *et al*., Tucson University Press, 69-108. [18] Schwandt C. *et al*. (2012) *Plan. Space Sci.*, **74**, 49-56. [19] Fredericks J. *et al*. (1991) LPSC XXII, p. 409. [20] Coombs C. R. *et al*. (1989) in *Workshop on Lunar Volcanic Glasses: Scientific and Resource Potential*, eds. J. W. Delano and G. H. Heiken, LPI Technical Report #90-02. [21] Hawke B. R. (1989) in *Workshop on Lunar Volcanic Glasses: Scientific and Resource Potential*, eds. J. W. Delano and G. H. Heiken, LPI Technical Report #90-02. [22] Jordan J. L. (1989) in *Workshop on Lunar Volcanic Glasses: Scientific and Resource Potential*, eds. J. W. Delano and G. H. Heiken, LPI Technical Report #90-02. [23] Dickinson T. (1990) in *Workshop on Lunar Volcanic Glasses: Scientific and Resource Potential*, eds. J. W. Delano and G. H. Heiken, LPI Technical Report #90-02. [24] Norman M. *et al.* (2012) *Aust. Journ. Earth Sci*. **59**, 291-306. [25] Norman M. D. *et a*l. (2013) 76th Met. Soc. Meeting, Abstract 5163. [26] Zellner N. E. B. *et al*. (2013) 44th LPSC, 2539.pdf. [27] Huang Y.-H. *et al*. (2018) *GRL*, **45**, 6805–6813. [28] Nguyen P. Q. and Zellner N. E. B. (2019) *Geosciences*, **9**(85). [29] Hess K. *et al.* (2019) 50th Lun. Plan. Sci. Conf. 3190.pdf.

Figure 1. Lunar glasses from Apollo 15 sample 15221, with sizes ≥200-µm. Image from [1].

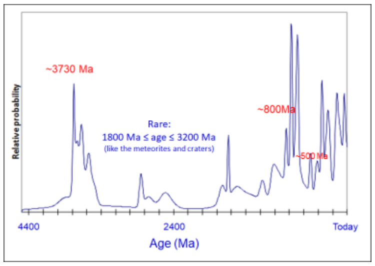

Figure 2. Lunar impact flux, as observed in lunar impact glasses. Modified from [4,5, 28].