

PALEOMAGNETIC FIELD INTENSITY AND MAGNETIC FIELD RECORDING CHARACTERISTICS OF APOLLO 15 GLASSES. K. A. Hess¹, R. R. Fu¹, N. E. Zellner², and S. M. Tikoo³, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA (kimberlyhess@fas.harvard.edu). ²Albion College, Department of Physics, Albion, MI. ³Rutgers University, Piscataway Township, NJ

Introduction: Despite recent advances, broad gaps remain in the understanding of the Moon's magnetic field history. To date, the primary source of data for paleomagnetic intensities has been limited to <20 Apollo rocks. These samples paint a picture of an internally generated dynamo with an average field of ~60-95 μT from 4.25-3.56 Ga that appears to have quickly declined to <~4 μT by 3.2 Ga [1]. Paleomagnetic measurements on a suite of samples representing a wider range of ages is necessary to provide a more complete record of the formation and decay of the lunar dynamo.

Along with whole rocks, the Apollo missions brought back samples of the lunar regolith. Contained in the loose soil are lunar glass shards and spherules with concentrations as high as 155 spherules in 1 gram of soil [2]. These lunar glasses may have a volcanic or impact origin. The volcanic sourced glasses have clearly defined ages of ~3700-3300 from the Moon's early resurfacing history [3]. The age range of the impact glasses is much wider from 3.9 Ga to 45 Ma [4]. Differentiating between impact and volcanic sourced glasses may be achieved using the $\text{MgO}/\text{Al}_2\text{O}_3$ and/or $\text{CaO}/\text{Al}_2\text{O}_3$ ratio. Using this technique, the majority of the spherules collected during Apollo regolith sampling have been determined to be impact in origin [5, 6].

Due to their wider geologic age range, impact glasses have the potential to fill in the gaps in our understanding of lunar dynamo history if they can be shown to be credible magnetic field recorders. Having cooled quickly following the cratering event, the quenched impact glass fragments and spherules contain fine-grained inclusions of metals and gasses from the lunar surface [4]. In principle, such small metal particles can record the ambient magnetic field during the time of glass formation. Joint paleomagnetic analysis and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the lunar glasses can therefore help define the overall history of the Moon's magnetic field beyond what is possible with whole rock samples.

In this study, we will analyze impact and volcanic glasses collected from the Apollo 15 regolith sample 15221 for paleomagnetic intensity, chemical composition, and geologic age. With the exception of two undated Apollo 14 lunar glass spherules from regolith sample 14163 [7], lunar samples of this size have not been analyzed to recover their magnetic moments

because they have expected natural remnant magnetization (NRM) moments of $<10^{-11} \text{ A m}^2$, which is near or below the noise limit of conventional magnetometers [8]. The availability of new imaging magnetometers, the SQUID microscope and the quantum diamond microscope (QDM), now allow the detection of such small magnetic moments.

Methods: We have obtained a sample set of 14 glasses from the Apollo 15 regolith sample 15221,21. Morphologically, these include 9 spherules and 5 shards. We first mounted and polished all glass samples in epoxy and characterized them using optical microscopy, finding that the glasses include 5 green, 8 red, and 1 black sample all ranging in size from 0.5mm to 1mm in diameter.

Following initial processing, we measured the natural remnant magnetization (NRM) of all 14 glasses using the QDM at the Harvard Paleomagnetism Laboratory and the SQUID Microscope at the MIT Paleomagnetism Laboratory. We then applied non-destructive three-axis alternating field (AF) demagnetization in steps of 5 mT from 5 mT to 50 mT to characterize the coercivity range of the NRM. Following the demagnetization sequence, we used anhysteretic remnant magnetization (ARM) acquisition experiments to obtain paleo-intensities for the samples, which can be used to establish that the samples were not exposed to secondary magnetization. The ARM acquisition experiments were also used to establish the recording limit of the glass samples, which quantifies the weakest paleomagnetic fields that could have been accurately recovered from these samples.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of glasses. The $^{40}\text{Ar}/^{39}\text{Ar}$ dating method has been used to successfully determine the ages of lunar impact and volcanic glasses with high precision, provided the sample contains enough potassium and has a composition that allows for effective retention of argon [4]. After the samples are analyzed for major and trace elements, they will be irradiated and analyzed for multiple Ar isotopes, including ^{40}Ar and ^{39}Ar . With this additional data set it will be possible to constrain the duration of high paleomagnetic field intensities on the lunar surface, if any, observed in the glasses.

Results: At this stage we have completed paleomagnetic analysis of 7 lunar glasses. Three of the

samples had very strong NRM moments relative to the strength of laboratory ARMs. Based on the strength of an ARM acquired in a 300 mT AC field and 200 μ T bias field ARM, all 3 spherules had paleointensities of ~ 1000 μ T (10 G), which is 20 times as high as the Earth's magnetic field. This result points to secondary contamination in a strong artificial magnetic field and therefore the NRM initially carried by the glass is not a record of the lunar magnetic field.

We then quantified the magnetic recording limit of two green glasses of likely volcanic origin using further ARM acquisition experiments. We completed ARM acquisition sequences on two lunar glass samples using 300 mT AC fields combined with 200, 100, and 50 μ T DC bias fields. The recovered magnetization directions agreed with those of the applied ARM field in the case of the 200 and 100 μ T bias fields and was ambiguous in the case of the 50 μ T bias field (Figure 1 and 2). Continuing experiments aim to quantify the degree of scatter in the recovered magnetic moment for bias fields ≤ 50 μ T and to extend these results to more glass samples. In any case, our preliminary results demonstrate that single lunar glass samples are likely capable of recording ancient lunar magnetic fields during the high field epoch, assuming ARM acquisition efficiencies are of order ~ 0.9 relative to a thermoremanent magnetization (TRM) as expected for fine-grained FeNi-bearing samples [9].

Going forward, we will proceed with AF demagnetization of the remaining glass samples. Based on the significantly lower magnetization intensities of some remaining samples (≤ 0.1 A/m), they are more likely candidates to have retained a TRM of ancient lunar magnetic fields.

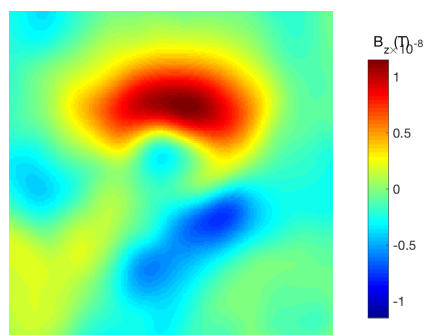


Figure 1, 300mT AC/100 μ T DC

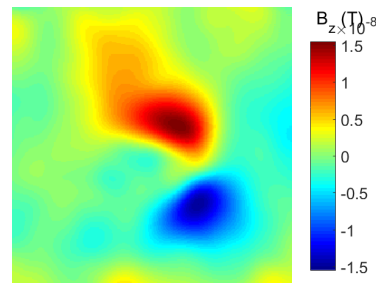


Figure 2, 300mT AC/200 μ T DC:

Conclusion: We have shown that lunar impact and volcanic glasses have the capability to record a paleomagnetic field with intensity ≤ 90 μ T. To date, the glass samples analyzed carry a strong secondary overprint. Ongoing AF demagnetization and ARM acquisition experiments will measure the magnetization of remaining samples, which have weaker magnetic moments and therefore may have avoided exposure to an artificial magnetic field. We will then conduct $^{40}\text{Ar}/^{39}\text{Ar}$ dating on lunar samples found to carry a credible lunar magnetization.

References: [1] Weiss, B.P. and Tikoo, S.M. (2014) *Science* 346.6214. [2] Culler, T.S., and Becker, T.A. (2000) *Science*. [3] Husain and Schaeffer, 1973; Podosek and Huneke, 1973; Huneke, 1978; Spangler et al., 1984. [4] Zellner, N. and Delano, J.W. (2015), [5] Delano, J. W. (1986), *JGR* 91.[6] Naney, M.T., Crowl, D.M., Papike, J.J., 1976 *Proc. Lunar Sci. Conf.* 7, 155–184. [7] Weiss, B.P., Lima, L.A. (2007) *JGR* 112. [8] Pearce, G.W. (1973) *LPSC Sup* 4, Vol. 3. [9] Lappe S.-C.L.L. et al. (2013) *GSG*.