ASSESSING THE RECENT IMPACT FLUX IN THE INNER SOLAR SYSTEM N. E. B. Zellner[1], R. Ghent[2], I. Daubar[3], J.-P. Williams[4], S. Marchi[5], N. C. Schmerr[6] [1]Department of Physics, Albion College, Albion, MI 49224 (nzellner@albion.edu), [2]Planetary Science Institute, Tucson AZ 85719, [3]Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI 02912, [4]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90024, [5]Southwest Research Institute, Boulder, CO 80302, [6]Department of Geology, University of Maryland, College Park, MD 20742.

Introduction: The lunar impact has flux is used to determine the impact rate in the inner solar system, from ~4.3 billion years ago onward. Formation and reset ages of lunar impact samples, geochemical data, crater chronologies, and dynamical models have been used together to construct the profile of the early impact flux (~4.3 Ga to 3.6 Ga; 1-5]. However, while some constraints are known, the profile of the impact flux remains debated and large gaps in the timeline exist. Establishing the recent lunar impact rate in particular would provide an understanding of the nature and origin of impactors contributing to the Moon's younger craters and impact samples. It would also provide information that would help put the Bennu, Ryugu, and Mars 2020 samples into a solar-system-wide context and provide a set of data points with which to compare the young terrestrial impact record.

Observations, Sample Data, and Constraints: The Apollo samples, specifically those collected at lunar volcanic and impact sites, are used to tie down the crater chronology curve that is used to estimate ages of surfaces throughout the solar system. The absolute model ages of craters on the Moon [6-9], along with impact samples presumed to have originated in specific young craters (e.g., Copernicus, ~800 Ma [10,11], Tycho, ~100 Ma [12,13], North Ray, ~46 Ma [14], Cone Crater, ~25 Ma [15], and South Ray, ~2 Ma [16] provide some guidance for estimating the recent impact flux. However, other observations call into question standard chronologies at the smallest diameters. These include: lunar rock abundances [17]; characteristics and populations of lunar "cold spot" craters [18,19]; lunar impact glasses [20; Figure 1]; terrestrial impact glasses [21] and craters; impactites in lunar breccias and lunar, martian, and asteroidal meteorites [22,23; Figure 1]; and *in situ* dating of martian craters [24,25]. Even younger impact craters, formed in the past decade, have been observed on the Moon [26,27] and Mars [28].

A variety of crater chronologies have been proposed [2,4,5, 29-32] and used to determine the absolute model ages of the Moon's young impact craters. Though the ages have been re-assessed, small amounts of variations of the impact rate cannot be resolved [7]. Of particular interest is to investigate whether or not the impact flux in past 3 Ga is constant or not [7,30,33,34], which is a crucial piece of information for predicting the number of sources a future seismic experiment would record at the Moon.

Correlated/Coincident Events: Multiple examples of connections between or among impact events on planetary bodies have been reported in the literature. A few are listed here:

- A global lunar impact event ~800 Ma has been proposed [35] based on $^{40}Ar/^{39}Ar$ ages of lunar impact glasses. Additional evidence for 800-Ma impacts has been seen in the H- and L-chondrites [36,37] and Chelyabinsk [38]. Formation of the Flora family of asteroids [39,40] or an impact in the Aedona family [4,42] may be responsible.
- The onset and termination of Snowball Earths, when ice covered nearly the entire surface (e.g., 660-710 Ma, 645-655 Ma), are not well-understood. Global melting may have been influenced by water vapor lofted into the terrestrial atmosphere during coincident periods of enhanced impact flux [43].
- Ages of fossil chondrite meteorites [e.g., 44] found in lower Ordovician (480 Ma) sediments and ages of several terrestrial impact craters [45] provide evidence for an enhanced impact flux that may be dynamically linked to the break-up of the L-chrondrite asteroid parent body [44,46-48]. The debris from these impacts may have initiated the mid-Ordovician ice age [49].
- Analysis of the spectrum of large craters with ages <650 Ma on both the Moon and Earth reveal evidence for a non-uniform cratering rate on both bodies, with a step-wise factor of 2-3 increase at ~290 Ma [50]. The observed lack of large terrestrial craters and other geological features older than 650 Ma (even on stable cratonic terrains) suggests rapid voluminous erosion possibly associated with Snowball Earth events [50,51].

However, interpretations that tie these events together within each proposed timeframe are limited by small data sets, lack of well-characterized terrestrial geologic evidence, low-resolution orbital data, and/or large uncertainties in derived or estimated sample or crater ages. More data in general are needed.

Resolving the Recent Impact Flux: Addressing the uncertainty in our understanding of the terrestrial

and/or solar system impact flux in the past 1.5 Ga requires a multi-prong approach. It should combine laboratory studies of multiple kinds of planetary samples, including meteorites that reveal clues about recent impacts on their parent bodies. Those data can forward-feed to dynamical simulations of events in the Earth-Moon system.

Further refinement of *in situ* dating techniques [52,53] and missions to return those data [54] are also important. Future lunar sample return missions and/or landed missions should have instruments capable of obtaining high-temporal resolution and accurate *in situ* ages. The site selection will be of critical importance and should include consideration of where the best samples with a diversity of ages that are well-linked to the regional geology occur. The sites should also best inform the least-well-characterized periods of lunar chronology.

Analyses of craters on multiple planetary bodies including Earth is imperative. High-resolution imaging of the Moon and other terrestrial bodies that have not been as well observed (e.g. Mercury) would clarify many issues. Specifically, repeat imaging with long baselines allows for the detection of craters forming today, which helps validate chronology models at one time point. Further work is also needed to quantify the small end of the impactor distribution represented by near-Earth objects (NEOs).

Finally, dynamical models should be implemented to reflect sample and orbital observational evidence. For example, a study of Apollo 16 ancient regolith breccias reported that, while chondritic impactors may have been common between 3.77 and 3.35 Ga, the Moon experienced impacts by a diverse group of impactors between 1.7 and 0.65 and <0.5 Ga [55]. Assessing the nature of those impactors would be a good test case.

References: [1] Morbidelli A. et al. (2012) *EPSL*, **355-356**, 144-151. [2] Marchi S. et al. (2009) *AJ*, **137**, 4936, 2009. [3] Marchi S. et al. (2012) *EPSL*, **325-326**, 27-38. [4] Neukum G. and Ivanov B. A. (1994), in *Hazards due to Comets and Asteroids*, T. Gehrels ed., University of Arizona Press, p.359. [5] Robbins: S. J. (2014) *EPSL*, **403**, 188–198 (2014). [6] Kirchoff M. et al. (2013) *Icarus*, **225**(1), 325–341. [7] Hiesinger H. et al. (2012) *JGR*, **117**, E00H10. [8] Morota T et al. (2009) *MAPS*, **44**(8), 1115–1120. [9] Williams, J.-P., et al. (2014) *Icarus*, **235**(C), 23–36. [10] Bogard D. D. et al. (1994) *GCA*, **58**, 3093–3100. [11] Barra F. et al. (2006) *GCA*, **70**, 6016-6031. [12] Arvidson R. et al. (1976) *Proc. Lunar Sci. Conf. 7th*, 2817-2832. [13] Drozd R. et al. (1977) *Proc. Lunar Sci. Conf. 8th*, 3027-3043. [14] Marti K. et al. (1973) *Proc. Lunar Sci. Conf.*, **4**, p.2037. [15] Crozaz G. et al. (1972) *Proc. Third Lunar Sci. Conf.*, *GCA Suppl.* **3**, pp. 2917-2931. [16] Drozd R. et al. (1974) *GCA*, **38**, 1625-1642. [17] Ghent R. R. et al. (2014) *Geology*, **42**, 1059–1062. [18] Bandfield, J. L. et al. (2014), *Icarus*, **231**, 221-231. [19] Williams, J. P. et al. (2018) *JGR*, **123**(9), 2380–2392. [20] Zellner N. and Delano J. (2015) *GCA*, **161**, 203-218. [21] Glass B. and Simonson B. (2013) *Distal Impact Ejecta Layers*, Springer. [22] Marchi S. et al. (2013) *Nature Geosci.*, **6**, 303-307. [23] Bogard D. D. (2011) *Chemie de Erde-Geochem.*, **71**, 207-226. [24] Werner S. C. et al. (2014) *Science*, 1–6. [25] Werner S. C. (2019) *MAPS*, **54** (5), 1182–93. [26] Speyerer, E. J., et al. (2016) *Nature*, **538** (7624), 215–18. [27] Oberst J. et al. (2012) *PSS*, **74**(1), 179–93. [28] Daubar I. et al. (2013) *Icarus*, **225**(1), 506–16. [29] Stoffler D. and Ryder G. (2001) *SSR*, **96,** 9–54. [30] Neukum G. et al. (2001) *SSR*, **96**, 55-86. [31] Hartmann W. K. (1970a) *Icarus*, **13**, 99-301. [32] Hartmann W. K. (1970b) *Icarus*, **12**, 131. [33] Bailer-Jones C. (2011) *MNRAS*, **416**, 1163-1180. [34] Williams J.-P. (2017) *MAPS*, **53**, 554–582. [35] Zellner N. E. B. et al. (2009) *GCA*, **73**, 4590-4597. [36] Wasson and Wang (1991) *Meteoritics*, **26**, 161-167. [37] Bogard D. D. (1995) *Meteoritics*, **30**, 244. [38] Righter et al. (2015) *MAPS*, **50**, 1790–1819. [39] Dykhuis et al. (2014) *Icarus*, **243**, 111–128. [40] Vokrouhlicky et al. (2017) *AJ*, **153**(4), 172–205. [41] Milani et al. (2017) *Icarus*, **288**2, 40–264. [42] Milani et al. (2019) *AA*, **622**, A4. [43] Koerberl C. and Ivanov B. (2019) *MAPS*, **54**, 2273–2285. [44] Schmitz B. et al. (2001) *EPSL*, **194**, 1–15. [45] Earth Impact Database (2011) http://www.passc.net/EarthImpactDatabase/New%20website_05-2018/Index.html. [46] Schmitz B. (2013) *Chemie der Erde*, **73**, 117–145. [47] Schmitz B. et al. (1997) *Science*, **278**, 88–90. [48] Thorslund P., et al. (1984) *Lithos*, **17**, 87–100. [49] Schmitz B. et al. (2019) *Sci Adv*. **5**, eaax4184. [50] Mazrouei S. et al. S. (2019) *Science*, **363**(6424), 253–257. [51] Keller et al. (2019) *PNAS* (2018). [52] Anderson S. et al. (2019) *50th LPSC*, 3277.pdf. [53] Cohen B. A., et al. (2014) *Geostand Geoanalyt Res*., **38**. [54] Lawrence S. et al. (2019) *50th LPSC*, 1110.pdf. [55] Joy K. et al. (2012) *Science*, **336**, 1426–1429.

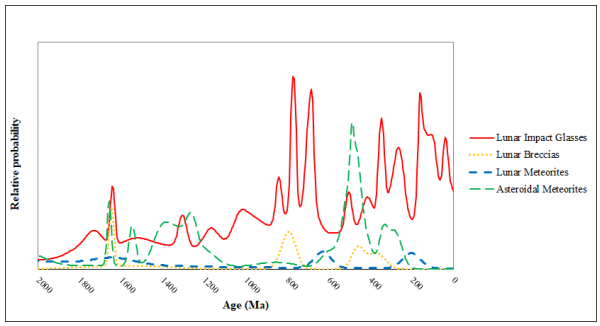

Figure 1. Recent impact episodes, as represented by a variety of solar system samples ($^{40}Ar/^{39}Ar$ ages). Modified from [20].