RETHINKING SOLAR SYSTEM BOMBARDMENT: NEW VIEWS ON THE TIMING AND DELIVERY OF LUNAR IMPACTORS N. E. B. Zellner[1] and J. W. Delano[2], [1]Department of Physics, Albion College, Albion, MI 49224 USA nzellner@albion.edu, [2]New York Center for Astrobiology, Department of Atmospheric and Environmental Sciences, University at Albany (SUNY), Albany, NY 12222 USA

Introduction: The Moon provides the most complete history of impact events in the inner Solar System since its formation ~4.5 billion years (Ga) ago. With samples from the Apollo missions and orbital data from Japanese, Indian, Chinese, European, and American orbiters, the Moon continues to provide clues for answers to questions about its impact flux, the timing of which is not well understood.

Apollo Sample Data and Impact Basin Stratigraphy: In contrast to the monotonic decline [1] in impactor flux, the "lunar cataclysm" [2] was proposed when no lunar impact samples older than 3.9 Ga were found in the Apollo samples. Based on the uncertainties in the dating of these lunar samples, estimates of the duration of this "spike" in impactors range from 100 to 200 million years (Ma) [3].

The ages of the largest basins on the nearside of the Moon have been used to time this supposed cataclysm. These basin ages were derived from Apollo samples presumed to be their ejecta, based on the orbital data available at the time. Serenitatis has been given an age of 3.893 ± 0.009 Ga [4], while Imbrium has an age of 3.85 ± 0.02 Ga [e.g., 3]. South Pole Aitken, because it is the largest lunar impact basin, has been interpreted as the oldest [5], but no Apollo or meteorite sample is known to be derived from that basin [but see 6,7].

Recent Analyses of Lunar Samples: In the past few decades, improved analytical instruments and techniques have led to more precise ^{40}Ar/^{39}Ar dating, and, along with ages derived from U-Pb, these new analyses show that some lunar impact melts [e.g., 8, 9], lunar zircons [10], and lunar meteorites [e.g., 11, 12] show evidence for impacts older than 3.9 Ga and as old as 4.3 Ga in some cases. Additionally, some lunar meteorite ages, within uncertainties [12], provide evidence for impact episodes younger than 3.9 Ga, implying that the impact flux may not have "spiked". Studies of lunar impact glasses [13] also show a preservation of a remnant population with ages >3.5 Ga.

Lunar Orbital Data: High-resolution data from the Lunar Reconnaissance Orbiter (LRO) show that the stratigraphic sequence of ejecta from the largest basins is not what we presumed from lower resolution Apollo and Ranger images. In two separate studies [14,15], impact ejecta presumed to be from Serenitatis were shown to be from Imbrium. Additionally, LRO altimeter data, along with gravity data from GRAIL, are providing evidence for old, eroded, and large quasi-circular depressions that may provide evidence for impacts older than 3.9 Ga [16].

Terrestrial Data: Evidence on Earth for this purported cataclysmic event remains elusive [but see 17], because siderophile elements (e.g., iridium) have not been found in the oldest sediments on Earth [18]. Evidence for multiple younger impact craters, however, has been found; crater ages are between 3.23 and 3.42 Ga [19].

Dynamical Models: Dynamicists have been modeling various impact scenarios (e.g., cataclysm, prolonged decline) that might serve to support the observational evidence. Planetary migration [e.g., 20, 21], differences in impactor populations [e.g., 22, 23], and/or disturbances in the asteroid belt [24] are the most likely culprits.

Conclusions: With these new lines of evidence from sample and orbital data, the timing and nature of the lunar impact flux is evolving. Understanding this record can be used to gain insights into how the Earth has been influenced by impacting events over billions of years.

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