AN EXTENDED EPISODE OF EARLY BOMBARDMENT IN THE INNER SOLAR SYSTEM: EVIDENCE FROM LUNAR SAMPLES AND METEORITES. M. D. Norman[1,2] and A. A. Nemchin[3], [1]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia (marc.norman@anu.edu.au), [3]Department of Applied Geology, Curtin University of Technology, Perth WA 6845 Australia (a.nemchin@curtin.edu.au).

Introduction: A spike in the flux of asteroid-size bodies traversing the inner Solar System and impacting the terrestrial planets at 3.9 Ga has become a keystone of recent models describing planetary dynamics [1], the chronology of planetary surfaces [2] and assessments of the potential habitability of early terrestrial environments [3,4]. Lunar samples provided the initial observational data that motivated this idea [5, 6], and the lunar cratering record now serves as a reference frame for the cratering chronology of Mars and inner solar system [7].

The absence of lunar impact melt breccias with ages between ~4.4 and 3.9 Ga has long been cited as evidence favoring a relatively low average impact flux during the interval between planetary accretion and the formation of many if not all of the lunar basins during a relatively brief episoce of late heavy bombardment from ~3.8 to 4.0 Ga [3]. However, large impact events on the Moon with ages ranging from 4.1-4.3 Ga have been inferred from recent dating of lunar zircons [8, 9] from previously unrecognized varieties of lunar impact melt breccias [10, 11], from clasts in fragmental lunar breccias [12] and from metamorphic lunar breccias (granulites) [13]. Here we summarize the lunar sample evidence for pre-cataclysm (i.e. older than 3.9 Ga) impact events on the Moon, and suggest that the basin-forming epoch likely spanned a significantly longer period of time than implied by the Cataclysm Hypothesis.

Impacts dated by lunar zircons: The U-Pb ages of most lunar zircons date the igneous crystallization of trace-element enriched magmas petrogenetically linked to the Procellarum-KREEP terrane [14]. However, some lunar zircons appear to have crystallized directly from KREEP-rich impact melts and therefore date the timing of impact melting directly. Primary zircons produced during crystallization of impact melt are found in lunar meteorite SAU169, which yielded an age of 3909 $\pm$ 13 Ma [15], and in a evolved (Si-rich) melt clast in lunar breccia 73217, which has an age of 4335 $\pm$ 5 Ma [9]. Zircons from Apollo 12 impact melt rocks 12032 and 12033 also have ages of 3914 $\pm$ 7 Ma [16] and together with SAU169 and U-Pb ages of apatite in Apollo 14 breccias [17] probably date the Imbrium basin-forming event at 3.91 Ga. The commonly quoted 3.85 Ga age of Imbrium based on ^{40}Ar-^{39}Ar dating of Apollo 15 impact melt breccias [18] is in agreement with the U-Pb ages after re-calibration for new monitor ages and revision of the K-Ar decay constants [12, 16].

Zircons that have lost their crystallinity (amorphic) or been recrystallized by shock also provide constraints on the ages of large lunar impacts. At least four different impact events with ages of 4333 $\pm$ 7 Ma (identical to the 73217 melt breccia age), 4307 $\pm$ 8 Ma, 4187 $\pm$ 11 Ma, and 4106 $\pm$ 9 Ma have been distinguished based on amorphic and shock recrystallized lunar zircons [9]. All of these impact ages are older than the canonical lunar cataclysm, and probably date large events based on the inferred crystallization depth of the parental magmas and the magnitude of the impact shock and heating heating necessary to recystallize lunar zircon [8, 9, 14].

Pre-Cataclysm lunar impact melt breccias: In addition to the zircon ages, anorthositic lunar breccia 67955 has been dated at 4.20 $\pm$ 0.02 Ga based on U-Pb dating of U-rich phases (zirconalite, apatite) [19], which is in agreement with the 4.20 $\pm$ 0.07 Ma ^{147}Sm-^{143}Nd mineral isochron age reported previously for that sample [10]. The texture and high levels of meteoritic contamination in this crystalline breccia indicates that it formed by slow cooling of a large body of impact melt, possibly related to a basin-forming event at 4.20 Ga. Recently, an impact melting event at 4.21 $\pm$ 0.13 Ga was proposed for breccia 67935 based on ^{187}Re-^{187}Os isochron data for separated metal and silicate phases of this rock [10]. This result is identical with the age of 67955 from the same locality, but results from other breccias studied by [10] show that ^{187}Re-^{187}Os isochrons are not a general feature of lunar melt breccias, raising the possibility that the metal in 67935 may be an artefact of this particular sample and might not date the impact melting that formed 67935.

Lunar granulites and clast-rich melt breccia clasts: Lunar granulitic breccias are metamorphic rocks that formed predominantly at or near the lunar surface during transient heating events most likely related to impacts. Some lunar granulitic breccias yield ^{40}Ar-^{39}Ar platueau ages of 4.1-4.3 Ga [8] but the question of partial equilibration of older components has bedeviled interpretions of these data [20]. Similar concerns over incomplete outgassing and lack of equilibration also apply to some fragment-laden melt-matrix clasts with apparent ^{40}Ar-^{39}Ar ages of ~4.1-4.2 Ga that are present in some lunar fragmental breccias [12]. Although the apparent argon ages of some lunar granulites and the fragment-laden melt breccia clasts do overlap with the well-defined ages of lunar zircons and 67955, it is difficult to define specific impact events based on these data.

Summary: The 'strong version' of the Cataclysm Hypothesis in which all lunar basins formed at 3.8-4.0 Ga is becoming increasingly untenable. A number of large, possibly basin-scale impact events with ages of 4.1-4.3 Ga have now been dated using lunar samples, in addition to the significant population of melt breccias that clearly formed at ~3.9 Ga. It appears that the Moon, and therefore Mars and Earth, experienced an extended phase of post-accretionary heavy bombardment rather than a single short, sharp spike of basin-forming impacts at 3.9 Ga (Fig. 1). An apparent change in impactor velocity recorded by Pre-Nectarian lunar crater populations also implies that all lunar basin formation were not produced during a single episode, but involved multiple populations of impactors [21]. Argon ages of brecciated eucrite meteorites, probably derived from asteroid 4Vesta, further suggest an extended phase of impact evolution that began by at least 4.1-4.2 Ga and continued until ~3.4 Ga [22], although the size of these impacts relative to those that created the lunar basins is not well determined. Possible implications of an extended episode of heavy bombardment for the environmental conditions on Mars and the early Earth, and for chronologies based on basin populations may need further consideration.

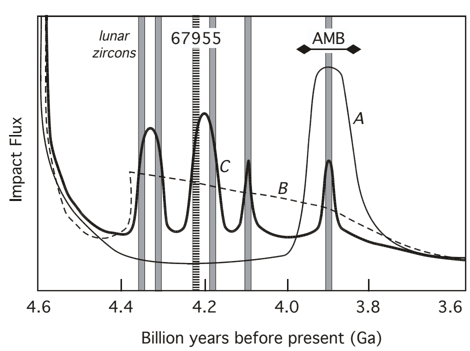

Fig. 1. Schematic impact flux curves implied by lunar sample data. Curve A is the canonical Cataclysm at 3.9 Ga; it is not consistent with recent results demonstrating a number of large impact events during the interval 4.10-4.35 Ga. Curves B and C illustrate alternative possibilities in which the pre-3.9 Ga impact flux was relatively steady (B) or episodic (C).

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