EVIDENCE FOR TWO IMPACTING POPULATIONS IN THE EARLY BOMBARDMENT OF MARS AND THE MOON.

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Motivating Problem. The sources of early bombardment for Mars and the Moon have long been debated [e.g., 1]. It is challenging to resolve this issue because (i) dynamical modelers are still struggling to understand the endgame of planet formation, which likely involved giant planet migration, and (ii) ancient crater records on Mars and the Moon, mostly examined using diameter $20 < D_{\text{crat}} < 150$ km craters, are not diagnostic enough by themselves to rule out different possibilities. Recently, however, new data for large $D_{\text{crat}} > 150$ km craters has become available via NASA missions [2, 3]. Here we use this information, new numerical simulations of giant planet migration [4], and new crater scaling laws [5] to compare and contrast their early bombardment signatures.

Early Bombardment Sources. Plausible sources for early inner solar system bombardment are leftover planetesimals from terrestrial planet formation [e.g., 6] and the depletion of small body reservoirs (e.g., primordial Kuiper and asteroid belts) by giant planet migration as discussed in the Nice model [e.g., 4, 7]. The former would have been recorded as soon as planetary surfaces were stable, while the latter could have hit early and/or late, depending on when the giant planets experienced an instability that reconfigured their orbits. Here we focus on main belt depletion, taking advantage of our latest Nice model simulations [4].

The shape of the main belt size-frequency distribution (SFD) is shown in Fig. 1 [8]. In our model runs, most depletion comes from the inner main belt ($a < 2.5$ AU); the central main belt is less depleted and the outer main belt is left largely in place. From a probability standpoint, most Mars/Moon impactors come from the inner main belt, where the impact ratio is ~10:1, respectively, and ~0.5% strike Mars. Overall, the primordial main belt loses roughly a main belt’s mass (i.e., $\sim 8000 \times 2, \div 2$) bodies with $D_{\text{ast}} > 10$ km.

Mars Bombardment. Using these numbers, we predict Mars was hit by $\sim 40 \times 2, \div 2$ $D_{\text{ast}} > 10$ km bodies from the main belt, with the impacting SFD having the same shape as the inner/main central main belt SFD from Fig. 1. To extend these SFDs to $D_{\text{crat}} < 3$ km, we assumed the main belt SFD followed the shape of the NEO SFD [9]; this is reasonable because most NEOs come from the main belt via the Yarkovsky effect [9] and the NEO SFD matches Vesta’s crater SFDs [5].

For Mars’s bombardment constraints, we first looked at $\sim 100 D_{\text{crat}} > 150$ km craters located predominately on its ancient southern highlands (Fig. 2) [2]. They cover 40-50% of Mars and were identified after an extensive geologic mapping effort. Buried/equivocal structures were excluded. Also plotted are 20 $< D_{\text{crat}} < 150$ km craters found near Hellas basin [10]. Hellas is perhaps the oldest largest basin to form after Mars’s surface was reset by the Borealis basin-forming event [11].

Intriguingly, the shapes of the main belt and Mars crater SFDs are the same (Figs. 1-2). Moreover, if we assume the crater scaling law function, $f$, is a simple ratio between crater and projectile diameters (i.e., $f = D_{\text{crat}} / D_{\text{ast}}$), and that $f \sim 24-30$, not only do the curves
Ancient basins/craters on lunar farside scaled to entire surface. They do not look like main belt SFD (Figs. 1-2). Younger lunar basins/craters are arguably a better match (e.g., craters near Nectaris basin in green).

**Lunar Bombardment.** The oldest lunar terrains (called Pre-Nectarian, or PN) are mostly located on the Moon’s farside [12-13]. Using the record of $D_{\text{crat}} > 150$ km craters identified in GRAIL data [3], we computed which regions that had the highest crater spatial densities. Collectively, these regions cover 70% of the farside and compare favorably to the PN terrains identified by [12-13]. The $D_{\text{crat}} > 150$ km craters located there are plotted in Fig. 3, with their numbers scaled to the entire lunar surface. Regions excluded include terrains near large young basins like Orientale, Hertzprung, and Moscoviense. A set of smaller PN craters ($20 < D_{\text{crat}} < 150$ km) are also plotted [14].

The two crater SFDs in Fig. 3 (blue curves) nicely fit together and yield a cumulative slope of $q = -2.07$ for $40 < D_{\text{crat}} < 600$ km. This value is much shallower than the $q \approx -3$ slopes seen for $D_{\text{crat}} < 20-30$ km in Fig. 1. Mars also shows no indication that it was hit by such crater SFDs in Fig. 2, and we argue the lunar craters plotted are not in saturation. We conclude that the lunar farside provides evidence for a different and likely older impactor population than that found on Mars.

Interestingly, younger $20 < D_{\text{crat}} < 120$ km craters found near Nectaris basin [14] (Fig. 3, green curve) are more consistent with the shapes seen in Figs. 1-2. This and related evidence suggests the Nectarian-era and younger basins/craters are potentially from main belt impactors, as suggested previously [e.g., 7].

Using Mars’s crater record as a benchmark (Fig. 2), a $\sim$10:1 impact ratio for Mars/Moon, and similar scaling laws for Mars/Moon, we predict that $\sim 30$ $D_{\text{crat}} > 150$ km craters should have formed on the Moon from main belt impactors. This compares to $\sim 180$ on the oldest PN terrains (Fig. 3). Accordingly, main belt depletion is a modest player in the net ancient bombardment of the Moon (30/180, or $\sim 17\%$), but should be more important for younger basins/craters. If standard scaling laws are instead used, the main belt’s contribution to lunar basins/craters is even lower [4].

**Implications.** Two “take away” messages are:

1. *Mars has a basin/crater SFD whose shape and absolute numbers are consistent with asteroids coming from the main belt via the Nice model, provided our crater scaling laws are reasonable.*

   If the Nice model’s giant planet instability occurred prior to Borealis basin formation, there is insufficient mass escaping out the main belt to reproduce the crater record seen in Fig. 2. Constraints from Martian zircons and highly siderophile elements indicate Borealis basin formed $\sim 4.5$ Ga [e.g., 15]. Because crater retention may be limited on Mars for tens of Myr after Borealis, we predict the instability occurred $< 4.45$ Ga.

2. *The most ancient lunar basin/crater SFD is different from that on Mars. This suggests two different impacting populations (one early and one late).*

   If the giant planet instability occurred $\sim 4$ Ga, a value that matches other bombardment constraints [16], our model runs indicate some Martian basin/craters likely formed from main belt asteroids escaping and striking between Borealis basin formation and the instability (i.e., the “doldrums” [15]). Prior to the instability, the Mars/Moon impact ratio is $\sim 7:1$, leaving more room for an increased number of lunar impacts than suggested above. The crater SFD produced would remain the same for all main belt impacts, though.

Finally, we predict the Moon was able to retain large basins/craters on its farside crust prior to the oldest crater ages on Mars (possibly $> 4.45$ Ga). This timing allows the Moon to be hit by leftover planetesimals or another impactor population not seen on Mars. These ages also constrain how long the older impactor population could exist in the terrestrial planet region.