EVIDENCE FOR TWO IMPACTING POPULATIONS IN THE EARLY BOMBARDMENT OF MARS AND THE MOON. W. F. Bottke[1], D. Nesvorny[1], F. Roig[2], S. Marchi[1], D. Vokrouhlicky[1,3]. [1]Southwest Research Institute and NASA's SSERVI-ISET Team, Boulder, CO (bottke@boulder.swri.edu) [2]Department of Astronomy, National Observatory, Rio de Janeiro, Brazil. [3]Institute of Astronomy, Charles University, Prague, Czech Republic.

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 < $D_{\rm crat}$ < 150 km craters, are not diagnostic enough by themselves to rule out different possibilities. Recently, however, new data for large $D_{\rm crat}$ > 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., ~8000 [×2, ÷2] bodies with $D_{\rm ast}$ > 10 km).

Mars Bombardment. Using these numbers, we predict Mars was hit by ~40 [×2, ÷2] $D_{\rm ast}$ > 10 km bodies from the main belt, with the impacting SFD having the same shape as the inner/central main belt SFD from **Fig. 1**. To extend these SFDs to $D_{\rm ast}$ < 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 ~100 $D_{\rm crat}$ > 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. Most are early to mid-Noachian in age, and their numbers were scaled to the entire Martian surface. Buried/equivocal structures were excluded. Also plotted are 20 < $D_{\rm crat}$ < 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., $f = D_{\rm crat} / D_{\rm ast}$), and that f ~ 24-30, not only do the curves

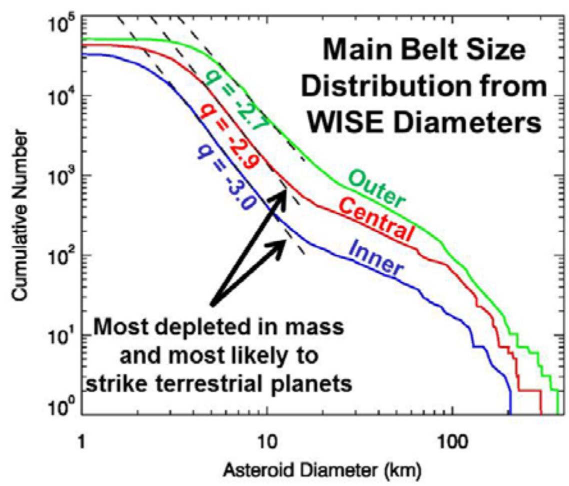

Fig. 1. Main belt SFD [8]. Planet migration has sharply depleted inner/central regions. The shallow/steep pattern for D < 100 km is a byproduct of collision evolution [9].

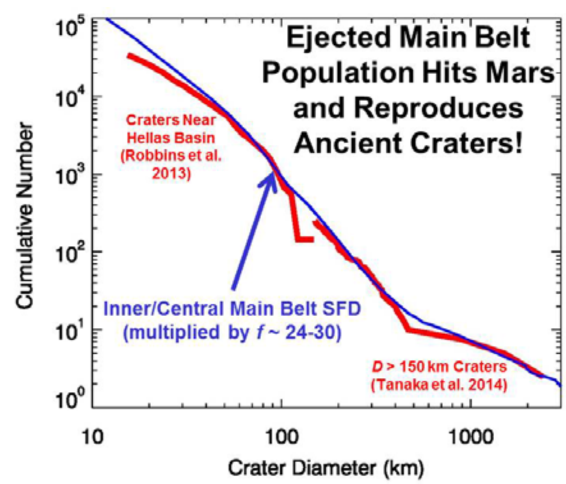

Fig. 2. Ejected main belt population hits Mars (SFD via **Fig. 1** and text). It reproduces ancient crater SFD scaled to entire surface, provided crater scaling law is f ~ 24-30.

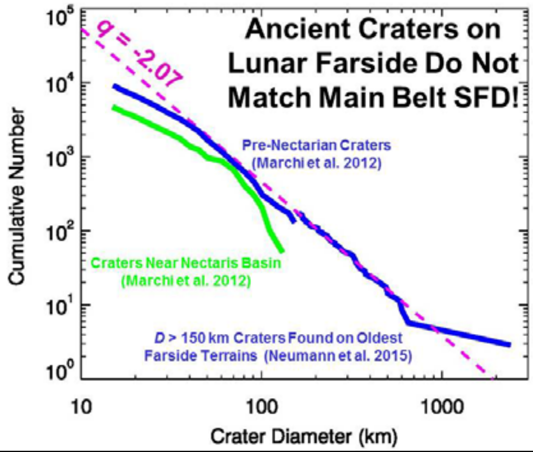

Fig. 3. Ancient basins/craters on lunar farside scaled to entire surface. They do not look like main belt SFD (**Figs. 1-2**). Younger lunar basins/craters are arguably a better match (e.g., craters near Nectaris basin in green).

match one another but they also yield the observed number of D > 300 craters (**Fig. 2**) from D_{ast} > 10 km impactors (i.e., ~40 [×2, ÷2]). The justification for this scaling law comes from empirical fits between the NEO SFD and craters formed on Venus, Mars, and the Moon over the last 3 Gyr [5]. Accordingly, main belt depletion via the Nice model can plausibly reproduce all of Mars's post-Borealis bombardment record.

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_{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_{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, Hertzsprung, and Moscoviense. A set of smaller PN craters (20 < D_{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_{crat} < 600 km. This value is much shallower than the q ~ -3 slopes seen for D_{ast} < 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_{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 ~10:1 impact ratio for Mars/Moon, and similar scaling laws for Mars/Moon, we predict that ~30 D_{crat} >150 km craters should have formed on the Moon from main belt impactors. This compares to ~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 ~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.*

(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 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 ~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.

If the giant planet instability occurred ~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 ~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.

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