NEW INSIGHTS INTO THE MARTIAN LATE HEAVY BOMBARDMENT

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Introduction. The late heavy bombardment of the inner solar system (LHB) was likely a byproduct of late giant planet migration (Nice model) [1]. As planetary resonances moved to new positions, they possibly destabilized a hypothesized extension of the asteroid belt between 1.7-2.2 AU, coined the E-belt [2]. This drove many E-belt asteroids into the quasi-stable Hungaria asteroid region, which in turn produced an extended period of bombardment. The singular nature of this LHB, triggered at 4.1-4.2 Ga, explains many constraints, including (i) the formation of Nectarian-era and younger lunar basins, (ii) the relatively young ages of many large lunar craters, (iii) the quantity and timing of terrestrial impact spherule beds between 1.7-3.7 Ga, and (iv) the ^{40}Ar-^{39}Ar shock degassing ages found in asteroid meteorites between 3.5-4.1 Ga [2-4].

A successful LHB model, however, must be applicable to all solar system worlds. Here we test the E-belt model by applying it to Mars's impact record.

The E-belt Bombardment of Mars. The E-belt impact flux model in **Fig. 1** shows projectiles making Chicxulub-sized impacts on Earth/Moon (roughly $D \sim 6$ km projectiles hitting at 22 km/s). These runs reproduce constraints (i)-(iv) above. Mars's impact flux is superposed here; its projectiles hit at 14 km/s, so they yield smaller craters. Long bombardment tails exist for all three worlds.

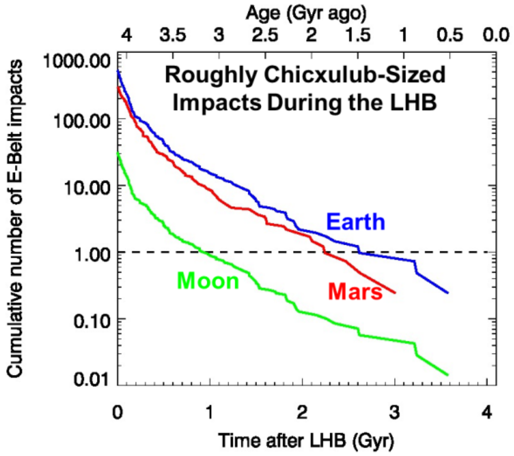

Fig. 1. E-belt asteroids hitting Earth, Moon, and Mars during the LHB. Note the long impact tails.

The ratio of E-belt asteroids striking Mars/Moon and Mars/Earth is ~10 and ~0.5, respectively. This shows Mars's LHB impact record integrated over its entire surface is quite similar to Earth's, though its craters are smaller because they hit at lower velocities. This makes Mars an excellent proxy to explore the precise nature of the LHB on our home world.

Mars's Impact Record. A recent geologic map of Mars [5] includes a list of ~100 $D > 150$ km craters (**Fig. 2**). Most are located on ancient highland terrains that cover ~50% of Mars. Scaling the number of $D > 150$ km craters by their coverage yields a worldwide population of ~200 ± 20 craters. We find ~4.5% of the E-belt population strikes Mars, so by applying crater scaling relationships [see 2], we predict the primordial E-belt population once had 4000-5000 $D > 7$-8 km bodies.

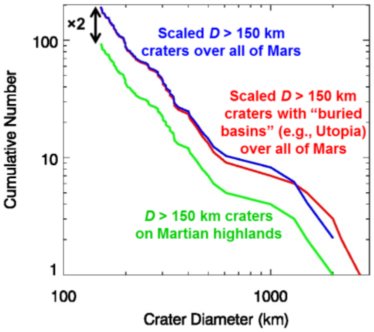

Fig. 2. Mars's $D > 150$ km craters.

These values are intriguing for several reasons:

- Only ~0.1% of the E-belt should still be left in the Hungaria population [2]. This leaves 4-5 $D > 7$-8 km Hungarias today, matching observations.
- Fig. 1 predicts Mars's LHB consisted of ~300 $D > 6$ km impactors. Scaling this value yields ~200 $D > 7$-8 km projectiles, enough to make all $D > 150$ km craters. Thus, nearly all sizable impacts younger than Utopia/Hellas are from the LHB.
- The basins Hellas and Utopia were made by $D > 100$-150 km impactors. Scaling 2 ± 1 impactors by the impact rate (4.5%), we estimate the E-belt population had 44 ± 22 such bodies. The main belt between 2.2-3.2 AU currently has ~200 $D > 100$ km asteroids, so the E-belt was once 22 ± 11% of the main belt. Interestingly, extending the main belt population into the E-belt zone yields 26%, an excellent match. This implies little mass was lost from the nominal main belt during the LHB, a prediction consistent with the latest "Jumping Jupiter" versions of the Nice model [e.g., 6].

Impactor size distribution of the LHB. A key issue concerns the nature of the LHB impactor size-frequency distribution (SFD). If the E-belt model is valid, the crater SFD on Moon/Mars should tell us about the primordial main belt SFD.

Up to now, constraints on LHB-era SFD have been almost entirely derived from the Moon, with new insights gleaned from impact models and GRAIL data (e.g., nearside basins are larger than farside ones because they formed in high heat flow regions [7]). Curiously, taken at face value, lunar crater constraints appear to work against the E-belt model, with [8] claiming an E-belt population with a main belt-like SFD produces 6× more large basins than those observed.

To explore this conundrum, we look to Mars's crater SFD, which should better sample the LHB than the Moon (i.e., the ratio of worldwide Mars/Moon impacts is ~10 and Mars's ancient cratered surfaces have twice the Moon's net surface area). Examining Fig. 2, we find it has (i) a "bump" of 9-10 basins between 600 < *D* < 3000 km and (ii) a power law with a cumulative slope ~ -2.5 to -4 for 150-200 < *D* < 450-600 km. This shape is reminiscent of main belt evolution models where "asteroids were born big" [9-11]. To recap, it was argued in [9-11] that the primordial main belt SFD was initially dominated by *D* > 100 km planetesimals, but collisional evolution produced a fragment tail with numerous *D* < 100 km bodies. We check this below.

Collisional Evolution in the E- and Main Belts. To model what happened to the E- and main belt SFDs between 4.1-4.567 Ga, we use the collisional evolution code *Boulder* [11]. Our initial SFD was chosen to be similar to those discussed in [9-11], with most mass placed in *D* > 100 km bodies. This SFD was then distributed into 15 annuli between 1.7-3.2 AU (0.1 AU wide). We assumed the (*e*, *i*) distribution of asteroids there was similar to today [2], with the mass between 2.2-3.2 AU set to a value near the current main belt's mass. To account for early outside influences that produce collisional evolution (e.g., impacting leftover planetesimals [12]), we assumed the equivalent of 4 to 6 Gyr of collisional grinding took place occurred between 4.1-4.567 Ga (See [9-10] for details).

A sample of our runs is shown in **Fig. 3**. The initial and evolved SFDs are summed from all annuli between 1.7-2.2 AU (E-belt) and 2.2-3.2 AU (main belt). Here more breakups occur in the E-belt; this is partly a byproduct of this zone's higher collision probabilities, with a few large stochastic breakup events producing a substantial fragment tail. The "bump" near *D* ~ 2-3 km is a byproduct of collisional evolution.

The model E-belt SFD in Fig. 3 does a good job of matching constraints from Moon/Mars. A key reason is that the E-belt starts with ~5 times fewer *D* > 100 km bodies than the main belt. This allows collisions in the E-belt to create a longer fragment tail between the *D* ~ 2-3 km and 100 km "bumps" than seen in the nominal main belt. As a result, we avoid producing too many large impact basins on the Moon [8].

Implications for Martian History. Here we highlight a few implications of our work for Mars:

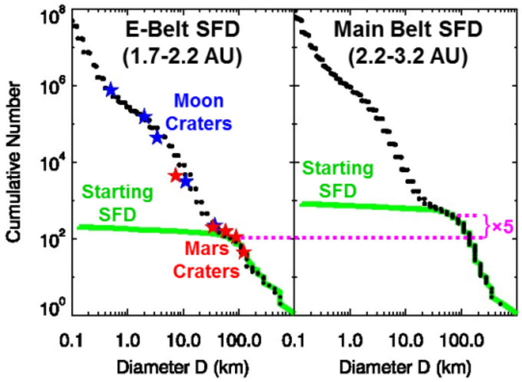

Fig. 3. Collisional evolution of E- and main belt SFDs.

- Mars's pre-LHB bombardment history has been erased except for Borealis basin [13] and remnant quasi-circular features [14]. It is possible many ancient impact features were removed by the slow formation of Mars's 50-125 km crust via basaltic volcanism (e.g., zircon data suggests new crust was being added until ~4.43 Ga [15]). We hypothesize that both Borealis and the remnant quasi-circular features formed in the pre-Noachian era.
- If the LHB accounts for all of the observed *D* > 150 km craters on Mars, the Noachian-era and the LHB had to start together at 4.1-4.2 Ga.
- The E-belt population continued to collisionally and dynamically evolve after it was driven onto planet-crossing orbits. Preliminary results indicate that modifications to this SFD may be able to explain the curious nature of the superposed crater SFDs found on younger Moon/Mars basins (e.g., lunar basins Imbrium/Orientale) [e.g., 16].
- Using our runs, we predict the youngest *D* ~ 220 km craters on Mars, Lyot and Galle, formed 2.6-2.8 Ga. These ages are the same as those derived from superposed crater counts, provided the new chronology of [17] is used (i.e., they counted lunar craters at Apollo landing sites using the latest LRO images). This work implies the burial of large craters like Utopia in the northern plains occurred prior to 2.6-2.8 Ga.

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