THE GREAT ARCHEAN BOMBARDMENT.

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The Late Heavy Bombardment (LHB) is often defined as a solar system-wide barrage of comets and asteroids that produced many young lunar basins, with the last one Orientale formed at ~ 3.7 Ga. Curiously, Archean and early-Proterozoic terrains on Earth, which post-date this era, also show signs of numerous LHB-sized blasts in the form of impact spherule beds, globally-distributed ejecta layers created by Chicxulub-sized or larger cratering events: at least 10, 4, and 1 have been found between 3.47-3.23 Ga, 2.63-2.49 Ga, and 2.1-1.7 Ga, respectively. Here we explore their origin via simulations of late giant planet migration in the presence of a hypothesized extension of the primordial asteroid belt between 1.7-2.1 AU [1]. These ejected "E-belt" asteroids are advantageous; not only are they are ten times more likely to hit the Earth and Moon than main belt ones, but they also decay far more slowly, with some evolving onto high inclination orbits like the observed Hungaria asteroids. By scaling the initial E-belt population from the observed Hungarias, we find that the E- and primordial main belts together make $\sim$ 12 lunar basins between 3.7-4.1 Ga, with the latter age occurring near the twelfth youngest lunar basin Nectaris. Older basins presumably come from other sources, such as planetesimals leftover from terrestrial planet formation processes. The key, however, is that expelled E-belt asteroids produce an extended LHB-era, with 15 basins made on Earth over the Archean as well as $\sim$ **60** and $\sim$ **4** Chicxulub-sized or larger craters on the Earth and Moon, respectively, between 1.7-3.7 Ga. These rates are sufficient to match both lunar and impact spherule bed constraints.

Model Runs. The best developed dynamical model of the LHB, referred to here as the Nice model [2], suggests that late giant planet migration drove resonances inward across the primordial main asteroid belt region. We use this framework to explore a possible missing source of late LHB-era impactors.

The main belt's inner boundary is currently set by the ν_6 resonance at 2.1 AU; objects entering this resonance have their eccentricities pumped up to planet-crossing values in < 1 My. Prior to the LHB, however, the giant planets and their resonances were in different locations [3], with the only remaining natural boundary being the Mars-crossing zone. Accordingly, it is plausible that the main belt once had an inner extension, or E-belt, that stretched as far as ~ 1.7 AU.

To track E-belt objects over 4.56 Ga, we integrated four sets of test bodies (see also [1]). In the *pre-LHB phase*, Venus-Neptune were placed on nearly-circular orbits consistent with Nice model initial conditions [4], while Mars was given 4 eccentricity values, with the maximum osculating value $e_{\rm MAX}$ reaching 0.025, 0.05, 0.12, and 0.17. Each E-belt population was composed of 1000 test bodies with $a = 1.7$-2.1 AU and e, i chosen from main-belt-like probability distributions [5], with the proviso that no test bodies were initially placed on Mars-crossing orbits. We integrated them for 0.6 Gy.

In the *LHB phase*, we assumed the Nice model occurred and placed all planets on their current orbits. This mimics the jump that Jupiter/Saturn had to have during the LHB [4]. We assumed Mars' eccentricity also reached its current value at this time by secular resonant coupling between the terrestrial/giant planets during planet migration. The remaining test bodies were tracked for 4 Gy, with the survivors cloned $10\times$ once 90% of the initial population was lost.

E-Belt Depletion. Overall, only 10-20% of the initial E-belt was lost over the first 0.6 Gy, and those that did escape had high collision probabilities and low impact velocities with the planets (e.g., for the Moon, median impact velocities before/after the LHB were 9 and 21 km/s, respectively). Interestingly, this velocity jump, when put through crater scaling laws, is enough to explain an increase in lunar basins sizes found near the transition between the Pre-Nectarian and Nectarian-eras [6]. This change may mark the starting time of the LHB.

Once the LHB begins, the E-belt decays to nearly 1/1000 its initial size, with the survivors driven into the Hungaria asteroid region at high i between 1.8-2.0 AU [7]. This region, bracketed by resonances, is dynamically "sticky"; objects finding a way in often take a long time to come back out. This allows the E-belt to produce a extremely long-lived tail of terrestrial planet impactors. *Thus, the E-belt makes Hungaria asteroids!*

Scaling from the observed Hungarias, we estimate that the E-belt's population just prior to the LHB was ~ 0.2-0.8 times that of the current main belt size distribution. The highest values of 0.6-0.8, correspond both to a nearly-circular Mars and a population density that matches that of the pre-LHB main belt, namely $4\times$ the current main belt population between 2.1-3.25 AU [3,4,8].

E-Belt Impactors. Numerical results show that E-belt asteroids are ten times more likely to hit the Earth and Moon than typical main belt asteroids. Thus, even a relatively small destabilized population can potentially make numerous impactors. Accordingly, we predict the

E-belt makes, on average, 9-10 lunar basins, with the combined contributions of E- and main belt making 12-13 lunar basins. This outcome suggests the start of the LHB is near the twelfth youngest basin Nectaris. As a check on this prediction, we compared crater counts on Nectaris terrains to our expected crater populations and found an excellent match.

Fig. 1 shows the Earth/Moon impact profile for our best-fit run. The top lunar curve was scaled to produce 9 LHB-era lunar basins, as calculated above. If correct, the lunar LHB lasted 400 My, with the end set by Orientale (3.72-3.75 Ga [6,10]). This puts the start of the LHB at 4.12-4.15 Ga. We consider this reasonable because several big things were happening at this time: (i) Nectaris basin may be 4.12 Ga [11,12], (ii) most ancient Apollo rocks affected by impacts have ages between 3.7-4.1 Ga [e.g., 12,13], (iii) H chondrites, eucrites, and ureilites have few Ar-Ar shock degassing ages between 4.1-4.4 Ga and many between ~ 3.3-4.1 Ga [e.g., 13,14], (iv) Martian meteorite AL84001 has a well-defined Lu/Hf age of 4.1 Ga [15], and (v) the young shergottites have unusual Pb-Pb ages that suggest their source region was disturbed ~ 4.1 Ga [16].

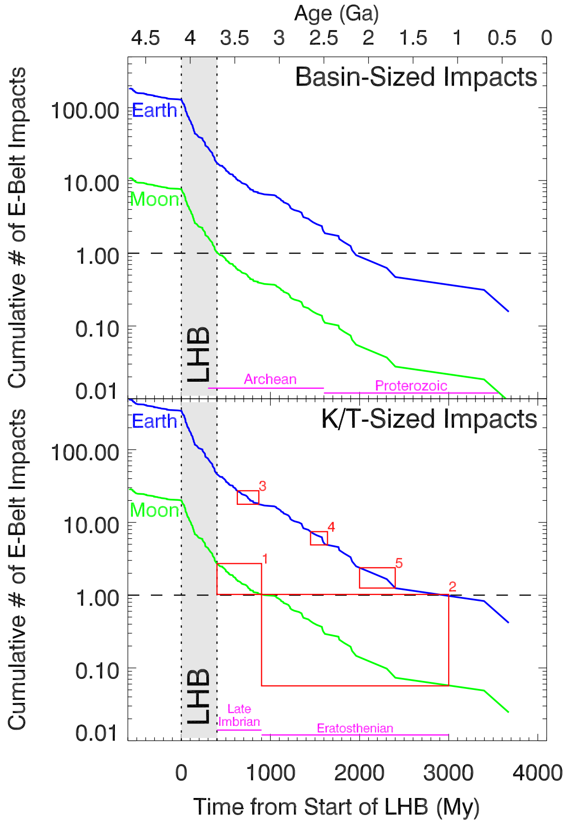

Figure 1. *The E-belt impactors that hit Earth/Moon and made basin-craters ($D > 300$ km) and K/T-sized craters ($D \sim 180$-300 km) over the last 4.6 Gy. During the Archean era, ~ 15 basins were produced on Earth. Boxes #1-#5 denote constraints described in text.*

To further test our model, we calculated the impact profile of K/T-sized craters formed on Earth/Moon after Orientale's formation. Models indicate comets and main belt asteroids are unlikely to make many K/T events at these times [2,5]. For the Late Imbrian era (**#1**; 3.7-3.2 Ga), there are 3 ± 2 such craters observed (i.e., Iridium, Humboldt, Tsiolkovskiy, with $D = 260$, 207, and 180 km, respectively), while for the Eratostenian era (**#2**; 3.2-1.0 Ga), there is 1 ± 1 observed (i.e., Hausen, with $D = 167$ km) [6]. Fig. 2 predicts 2 ± 1 and 1 ± 1 model K/T events should have taken place in these intervals, respectively, in agreement with observations.

On Earth, we predict that many tens of K/T-sized or larger events took place during the Archean-Proterozoic. These events are large enough that we can compare our model results to terrestrial spherule beds, a byproduct of such impacts that vaporize silicates and distribute melt droplets across the planet [17,18]. Observations indicate 10 ± 3 beds exist between 3.47-3.23 Ga (**#3**), 4 ± 2 beds exist between 2.63-2.49 Ga (**#4**), 2 ± 1 craters/beds exist between 2.1-1.6 Ga (**#5**), and 0 ± 1 crater/beds have yet been found between 1.6-0.6 Ga. Over the same time intervals, our model results are essentially identical: 9 ± 3, 3 ± 2, 1 ± 1, and 1 ± 1, respectively.

Implications. We predict that the terrestrial LHB produced ~ 15 basins and ~ 60 K/T-sized craters over the Archean and into the Proterozoic. Moreover, some of these impacts were likely Imbrium-sized [18]! The LHB tail likely produced the craters Vredefort (2.02 Ga) and Sudbury (1.85 Ga) [10]. Related impact profiles, scaled by collision probabilities and velocities, should also exist on Mercury, Mars, and possibly even Venus.

Impact cessation also produces eerie coincidences (e.g., the "Great Oxidation Event" [19] occurs once basin-sized impacts end at 2.5 Ga; the oceans enter into a Gy-long euxinic state [20] when all big impacts end at 1.85 Ga). Do connections exist? *The game is afoot!*

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