THE GREAT ARCHEAN BOMBARDMENT, OR THE LATE LATE HEAVY BOMBARDMENT. W. F. Bottke[1], D. Vokrouhlický[1,2], D. Minton[1], D. Nesvorný[1], A. Morbidelli[1,3], R. Brasser[1,3], B. Simonson[4], *(1) Center for Lunar Origin and Evolution (CLOE), NASA Lunar Science Institute, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, Colorado 80302, USA; bottke@boulder.swri.edu , (2) Institute of Astronomy, Charles University, V Holesovickach 2, CZ-18000, Prague 8, Czech Republic, (3) Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, B.P. 4229, 06304 Nice Cedex 4, France, (4) Geology Dept., Oberlin College, Oberlin, OH 44074 USA* .

Motivation. Last year, we argued the E-belt population, a putative part of the primordial asteroid belt that once existed between $a \sim$ 1.7-2.1 AU, was the missing link to the lunar Late Heavy Bombardment (LHB) [1]. The problem was that this scenario, while compelling in many ways, lacked a "smoking gun" to set it apart from other possible LHB components (e.g., leftover planetesimals in the terrestrial planet region, comets, ejected main belt asteroids). *Here we solve this by showing very late E-belt impacts match a range of Earth/Moon data.*

In our model, E-belt asteroids, stable prior to the LHB, were largely driven onto planet-crossing orbits when giant planet migration in the Nice model [2] pushed the ν_6 resonance across the asteroid belt and into its current location near 2.1 AU [2-4]. The depletion of the E-belt not only produced numerous Hungaria asteroids, some which still survive today, but it also created a long-lived tail to the LHB. As shown below, this population can produce (i) most Nectarian and Imbrian-era lunar basins, (ii) the right number of Hungaria asteroids, (iii) the right number of K/T-sized lunar impacts over the Late Imbrian-Eratosthenian eras, and (iv) the right number of impact-generated spherule beds produced on the Earth within well-searched Archean-Proterozoic terrains. *No other existing LHB model can match these constraints! Consequently, we predict the Archean Earth was blasted again and again by basin-forming impactors.*

Model Setup. 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, while Mars was given 4 eccentricity values, with the maximum osculating value e_{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. Fig. 1 shows how the E-belt evolves in our best-fit case, where pre-LHB Mars had a nearly-circular orbit ($e_{\mathrm{MAX}} = 0.025$). Only 10% 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 11 and 24 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.

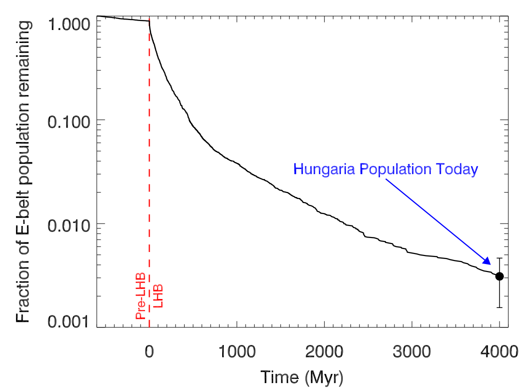

Figure 1. *Depletion of the E-belt for our best-fit case, where Mars was on a nearly-circular orbit prior to LHB ($e_{\mathrm{MAX}} = 0.025$ for $t < 0$ My).*

Once the LHB begins, the E-belt decays to 0.003 ± 0.0015 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!*

The existing Hungarias constrain the initial E-belt population. Assuming there are 5 ± 2 Hungaria asteroids large enough to form lunar basins today ($D >$ 8-10 km) [7], we predict the E-belt once held 2000 ± 1000 basin-forming projectiles. This value agrees with estimates of the predicted orbital density of main belt asteroids that existed just prior to the LHB, where the asteroid belt was roughly twice its current population [3,4,8].

E-Belt Impactors. Using these values, and our result that $\sim 0.4\%$ E-belt test bodies hit the Moon, we predict the E-belt created 8 ± 3 LHB-era lunar basins, with 2 ± 1 being Imbrium or Orientale-sized. Considering that

3 ± 2 lunar basins should come from the classical main belt (i.e., the above population combined with impact probabilities from [5]), the E- and main belts together should produce the 12 observed Nectarian/Imbrian-era basins [6]. This limits the scope of the LHB, and probably forces early Pre-Nectarian basins to come from elsewhere (e.g., leftovers planetesimals [9]).

Fig. 2 shows the Earth/Moon impact profile for the Fig. 1 run. The top lunar curve was scaled to produce 7-8 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 $\sim$ 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].

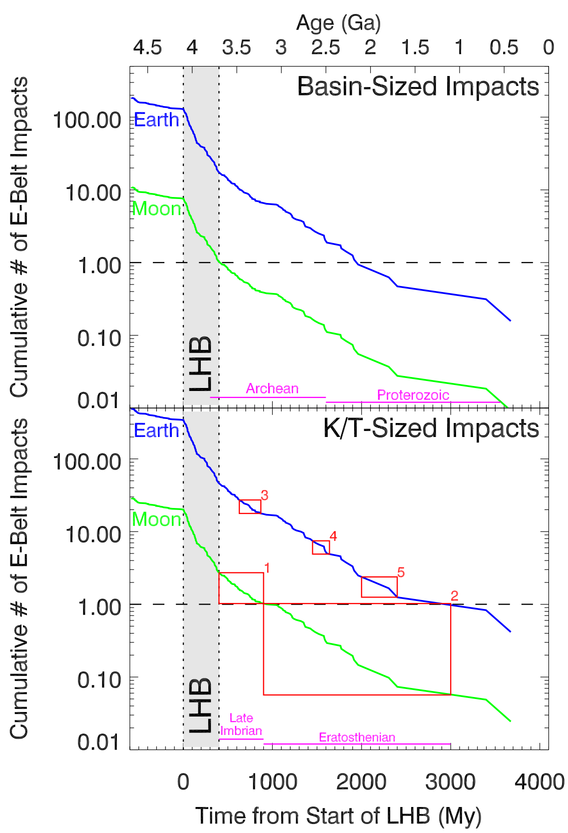

Figure 2. *The E-belt impactors that hit Earth/Moon and made basin-craters ($D > 300$ km) and K/T-sized craters ($D \sim 180$-300 km) over the last 4.6 Gy. During the Archean era, ~ 15 basins were produced on Earth. Boxes #1-#5 denote constraints described in text.*

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 7 ± 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 ± 4 basins and 30 ± 5 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!*

Finally, we infer that Mars (i) formed on a nearly-circular orbit and (ii) was excited during the LHB-era. Not only can these critical constraints be used to test planet formation and LHB models, but they may also change how we view the Early Noachian era.

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