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An Archaean heavy bombardment from a destabilized extension of the asteroid belt

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The barrage of comets and asteroids that produced many young lunar basins (craters over 300 kilometres in diameter) has frequently been called the Late Heavy Bombardment[1] (LHB). Many assume the LHB ended about 3.7 to 3.8 billion years (Gyr) ago with the formation of Orientale basin[2,3]. Evidence for LHB-sized blasts on Earth, however, extend into the Archaean and early Proterozoic eons, in the form of impact spherule beds: globally distributed ejecta layers created by Chicxulub-sized or larger cratering events[4]. At least seven spherule beds have been found that formed between 3.23 and 3.47 Gyr ago, four between 2.49 and 2.63 Gyr ago, and one between 1.7 and 2.1 Gyr ago[5–9]. Here we report that the LHB lasted much longer than previously thought, with most late impactors coming from the E belt, an extended and now largely extinct portion of the asteroid belt between 1.7 and 2.1 astronomical units from Earth. This region was destabilized by late giant planet migration[10–13]. E-belt survivors now make up the high-inclination Hungaria asteroids[14,15]. Scaling from the observed Hungaria asteroids, we find that E-belt projectiles made about ten lunar basins between 3.7 and 4.1 Gyr ago. They also produced about 15 terrestrial basins between 2.5 and 3.7 Gyr ago, as well as around 70 and four Chicxulub-sized or larger craters on the Earth and Moon, respectively, between 1.7 and 3.7 Gyr ago. These rates reproduce impact spherule bed and lunar crater constraints.

When a large impactor strikes the Earth, it produces a vapour-rich ejecta plume containing numerous sand-sized melt droplets, most of which rise above the atmosphere. Eventually the droplets cool and fall back, forming a global layer that can be several millimetres to many centimetres thick for roughly Chicxulub-sized or larger impact events[4]. These layers have been identified in particular Archaean and early Proterozoic terrains that have been extensively searched, although preservation biases and incomplete sampling are still possibilities. The characteristics of the layers and the spherules themselves suggest that they are distal rather than proximal ejecta. They potentially provide us with a comprehensive record of large ancient impact events, even if their source craters were eliminated long ago.

Although the precise projectile size needed to form a global spherule bed is unknown, all Archaean and early Proterozoic beds are as thick as or thicker than those associated with the 65-million-year-old, 180-km-diameter Chicxulub crater. In comparison, the 35-million-year-old, 100-km-diameter Popigai crater, perhaps the second-largest crater known from the Phanerozoic, formed a distal spherule bed that is less than 0.1 mm thick[6,9]. Spherule beds as thin as that have yet to be detected on ancient terrains.

The known ancient beds argue for an intense, protracted phase of late terrestrial bombardment[5–9]. Curiously, these enormous blasts have no obvious source, even though many occurred relatively soon after the formation of the 930-km-diameter lunar basin Orientale (see ref. 13, for example). This makes us suspect that a key aspect of the LHB has been missed.

The best-developed dynamical model of the LHB, referred to here as the Nice model[1,10], suggests that late giant planet migration drove resonances inward across the primordial main asteroid belt region. This event not only pushed numerous asteroids onto planet-crossing orbits, but also set up the current resonance structure of the main asteroid belt[11,12]. We use this framework to explore a possible lost source of late-LHB impactors.

The main asteroid belt's inner boundary is currently set by the ν_6 secular resonance at 2.1 AU (one astronomical unit is approximately the Earth–Sun distance); objects entering this resonance have their eccentricities pumped up to planet-crossing values in less than a million years[16]. Before the LHB, the giant planets and their associated secular resonances were in different locations, with the only remaining natural inner boundary being the Mars-crossing zone. Accordingly, the main asteroid belt may have once stretched into the E-belt zone as far as 1.7 AU.

To determine what would have happened to E-belt objects before and after planet migration, we tracked four sets of 1,000 model asteroids, with the population started with semimajor axes between 1.7–2.1 AU and main-asteroid-belt-like eccentricities and inclinations (Fig. 1a). In the pre-LHB phase, we assumed Nice-model-like initial conditions for the planets: Venus and Earth were on their current orbits, while the giant planets were on circular and nearly coplanar orbits between 5.4 and 11.7 AU (ref. 12). Our primary variable was the initial eccentricity of Mars, which conceivably could have been different at this time[17]. We set its maximum osculating value to $e_{\max}^{\mathrm{Mars}} = 0.025$, 0.05, 0.12 (its current value) and 0.17. We found most of our test asteroids were stable for 0.6 Gyr; losses were less than 15% for all but the $e_{\max}^{\mathrm{Mars}} = 0.17$ run (Figs 1 and 2). The bodies that did escape generally came from the periphery of the Mars-crossing zone, where they were perturbed onto planet-crossing orbits via interactions with Mars.

Next, in the LHB phase, the giant planets and their resonances were assumed to migrate to their current orbits in less than a million years. This behaviour was approximated in our model by instantaneously 'jumping' the giant planets to their current orbits. Numerical models show that resonances must have swept rapidly across the primordial main asteroid belt from the outside in, depleting it by about 75% (refs 11–13). They may also have allowed Mars to achieve its current orbital eccentricity via secular resonant coupling between the terrestrial and giant planets[17].

The sudden appearance of the ν_6 secular resonance at its current location, along with related resonances in the same region, destabilized E-belt asteroids by exciting their eccentricities and inclinations (Fig. 1b). Over the next 4 Gyr, these effects drove nearly all E-belt asteroids onto planet-crossing orbits (Fig. 2). En route, many passed through or near the Hungaria asteroid region, located at high inclinations between 1.8–2.0 AU (Fig. 1b)[14,15].

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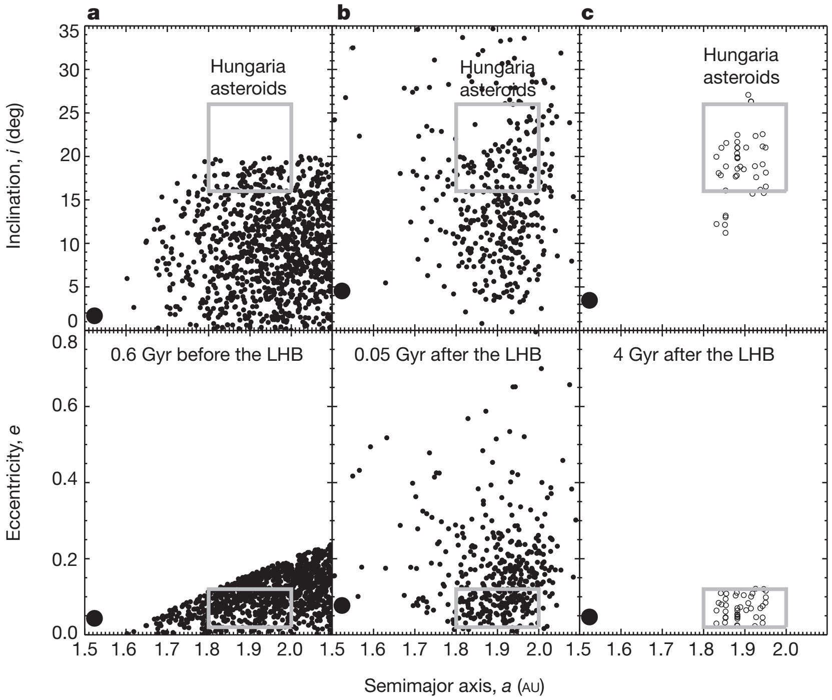

Figure 1 | Snapshots of the evolution of the E-belt population over time. **a**, 0.6 Gyr before the LHB. Here the filled circles show 1,000 randomly created test asteroids. They were selected according to a uniform distribution of semimajor axes a at 1.6–2.1 AU and a main-asteroid-belt-like Gaussian distribution in eccentricity e and inclination i, the latter having peaks at 0.15° and 8.5°, respectively, and standard deviations of 0.07° and 7°, respectively[13]. All test bodies initially placed on Mars-crossing orbits were rejected, and almost no objects achieved $a < 1.7$ AU. This yielded a population that was equivalent to 16% of the primordial main-asteroid-belt population between 2.1 and 3.25 AU. The planets were started on their pre-LHB orbits as defined in the main text, with $e_{\mathrm{max}}^{\mathrm{Mars}} = 0.05$. All bodies were tracked using the symplectic integration code SWIFT-RMVS3[29]. The large black circle is Mars. **b**, 0.05 Gyr after the start of the LHB. The planets are now on their current orbits. The population has dropped from 83% just before the LHB to 44% now. Many bodies have been driven onto orbits similar to those of the Hungaria asteroids (grey box; $1.78 < a < 2.0$ AU; $e < 0.15$, and $16° < i < 26°$; refs 14 and 15). **c**, 4 Gyr after the start of the LHB. The open circles are 41 clones of the original test asteroids and represent 0.14% of the original population. Our clones were created by adding a uniformly distributed random number between -1×10^{-6} AU and $+1 \times 10^{-6}$ AU to each of the position coordinates of our test bodies at a set time. Here the surviving test bodies were cloned ten times when 90% of the initial population was lost and three times once 90% of those clones were lost. Most reside in the Hungaria region.

The Hungaria population is the quasi-stable reservoir of small asteroids closest to the terrestrial planet region. Bracketed by multiple resonances, the region is dynamically 'sticky'—objects finding a way in often take a long time to come back out. This is reflected in our model runs, with our non-planet-crossing survivors after 4 Gyr always found on Hungaria-like orbits (Fig. 1c). We infer from this that if the initial E belt were large enough, it could have produced the Hungaria asteroids.

The current Hungaria population is comprised of a single E-type asteroid family, with E-types thought to have enstatite chondrite-like surfaces, set among a diverse background asteroid population (for example, E-, X-, S- and C-type asteroids)[14,15]. By accounting for their expected lunar impact velocities, which can be quite high (20% hit at over 30 km s^{-1}), we estimate that the Hungaria asteroids have 4 ± 2 objects capable of forming basins. This is tiny compared to the 7,500 or so that exist in the main asteroid belt[18] (see Supplementary Information).

Approximately 0.1–0.4% of our E-belt asteroids found refuge in the Hungaria region (Fig. 2). These values are probably upper limits; additional objects may have been eliminated by collisional evolution or migration onto planet-crossing orbits through a combination of Yarkovsky thermal forces and resonances[19]. We apply a depletion factor of 1.5 to account for these effects. Scaling from the known Hungaria asteroids, we estimate that the E belt's population just before the LHB was approximately 0.2–0.8 times that of the current main-asteroid-belt population[18]. Interestingly, the larger values yield a population density consistent with the primordial main asteroid belt just before the LHB[13]. This suggests that the E belt does not need to be exceptional to reproduce the Hungaria asteroids.

We find that a combination of our $e_{\mathrm{max}}^{\mathrm{Mars}} = 0.025$ and 0.05 runs produce, on average, nine or ten lunar basins during the LHB (see Supplementary Information). The main asteroid belt's contribution is about three, so together we get 12 or 13 lunar basins. The E belt dominates, despite its small size, because its asteroids have a probability of hitting the Earth and Moon that is ten times higher than those originating in the main belt[13]. In an end-member model, where E-belt and main-belt asteroids produce all of the lunar LHB, this would place its start near the formation time of the Nectaris basin[2,3]. As a check, we compared crater counts on Nectaris terrains to our expected crater populations and found an excellent match (see Supplementary Information). This could imply that comets are a minor player in the bombardment of the Earth and Moon during the LHB, as suggested by certain lines of evidence (such as the shape of the lunar crater size frequency distributions[20] and the inferred nature of basin projectiles[21]; see Supplementary Information).

Our LHB-era lunar basins form over an approximately 400-million-year interval, much longer than previous estimates[1] (Fig. 3). Thus, if the Orientale basin formed 3.7–3.8 Gyr ago, the LHB starting time should be 4.1–4.2 Gyr ago. These ages are intriguing because many lunar samples were modified by ancient impact heating events between 3.7 and 4.1 Gyr ago[22,23]. Similarly, in the asteroid belt, ^{39}Ar–^{40}Ar shock degassing ages for eucrite and H-chondrite meteorites show a paucity of ages 4.1–4.4 Gyr ago and numerous ages 3.5–4.1 Gyr ago[23,24]. For Mars, the data are meagre, but it is interesting to note that the crystallization age of Martian meteorite ALH84001 is about 4.1 Gyr ago[25]. The Martian shergottite source region also appears to have been disturbed at the same time[26].

Lunar basins and craters formed before 4.1–4.2 Gyr ago would presumably come from leftover planetesimals in the terrestrial planet region[27] and pre-LHB refugees from the primordial E belt and main

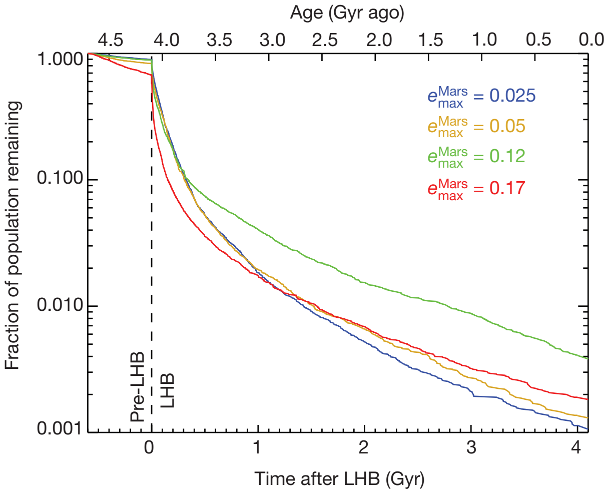

Figure 2 | Decay curves for our E-belt runs before and after the LHB. The blue, gold, green and red lines correspond to the different maximum eccentricities of Mars before the LHB, with $e_{\rm max}^{\rm Mars} = 0.025$, 0.05, 0.12 (current value) and 0.17, respectively. The test asteroids corresponded to starting E-belt populations with 18%, 16%, 9.3% and 5.4% of the primordial main-asteroid-belt population, respectively. Many asteroids eliminated before the LHB had orbits near the Mars-crossing region; they were scattered onto planet-crossing orbits via Mars perturbations. The $e_{\rm max}^{\rm Mars} = 0.12$ run was found to decay more slowly than the other runs because a larger fraction of its test asteroids were dynamically pushed near or through the quasi-stable Hungaria region. The effects of collisional evolution[18] and non-gravitational (Yarkovsky) forces on the objects[19] were not included, although they must affect our results. The former is most likely to affect the pre-LHB phase when the initial populations were massive. Tests for the latter indicate the amount of additional depletion produced for objects over 10 km in diameter in the LHB era is less than a factor of two, although it is more substantial for smaller asteroids. Taken together, we estimate that an extra depletion factor of 1.5 should reasonably account for these effects, though we consider this value to be conservative. In addition, although these decay rates do not suffer from small-number statistics, the real population does (that is, only 4 ± 2 basin-forming projectiles now exist in the current Hungaria population). Using a Monte Carlo code to track asteroid depletion, we find that our estimates of the initial E-belt population could easily vary by an additional factor of two (see Supplementary Information). If these factors worked in the right direction, it could allow our more eccentric Mars cases to also match LHB constraints.

asteroid belt (Fig. 3). They would have hit the Moon while the giant planets resided on nearly circular, largely coplanar orbits, with inner Solar System resonances too weak to produce the same degree of dynamical excitation as observed today among near-Earth asteroids. This result is reflected in our model lunar impact velocities, whose median values double from 9 km s^{-1} to 21 km s^{-1} once the LHB begins (see Supplementary Information).

Evidence for such a velocity change may exist on the Moon. Lunar crater size distributions on Nectaris terrains are found to have the same basic shape as those on the most ancient lunar terrains with diameters between 20 km and 150 km, but Nectaris craters are larger by 30–40% (ref. 28). This shift is consistent with impact velocities in the LHB-era increasing by a factor of about two (see Supplementary Information).

Our model results also demonstrate the need for an LHB. The E-belt model runs shown in Fig. 2 have steep decay rates as the LHB begins, but they then transition to shallow ones for the last billion years. This implies that shifting the start of the LHB to early Solar System times, say 4.5 Gyr ago, would only increase the size of the primordial E-belt population by about 30%, because it still has to match constraints from the current Hungaria population, but it would take away the E belt's ability to produce late lunar basins. Accordingly, if the giant planets reach their current orbital configuration much earlier than 4.2 Gyr ago, the E belt and main asteroid belt cannot form lunar basins like Imbrium and Orientale at 3.7–3.9 Gyr ago.

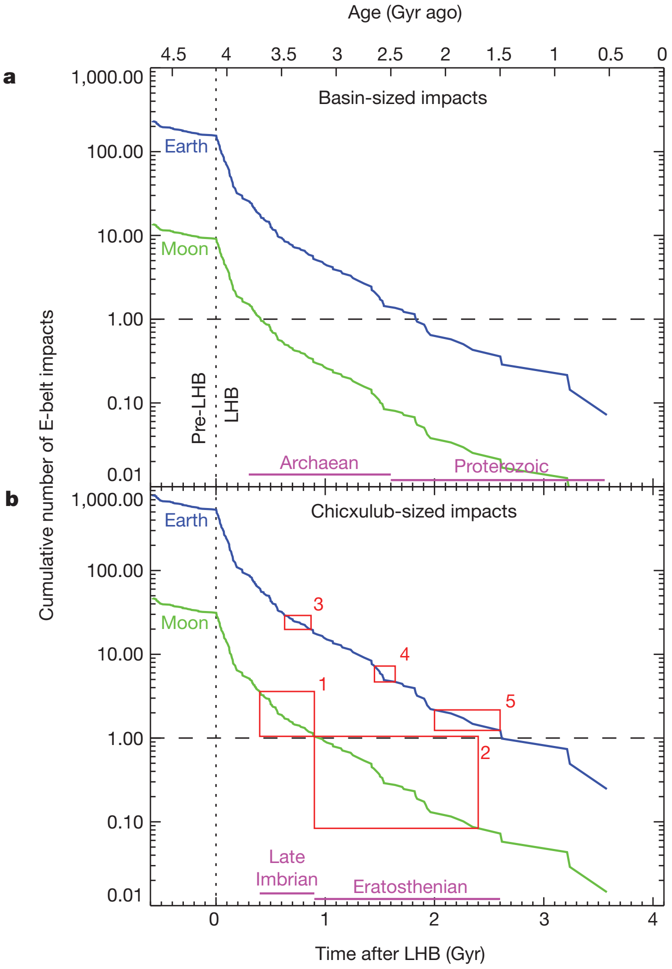

Figure 3 | The E-belt impactor flux on the Earth and Moon. a, The number of E-belt impacts making basin-sized craters (diameters over 300 km) on Earth and the Moon. The curves represent the combined results of the $e_{\rm max}^{\rm Mars} = 0.025$ and 0.05 runs. They were normalized assuming that about nine lunar basins form during the LHB and that the age of the last lunar basin (Orientale) is 3.7 Gyr ago[3]. **b**, The number of E-belt impacts making Chicxulub-sized craters (diameters over 160 km) on Earth and the Moon. The curves were scaled up by a factor of 3.4, approximately the ratio of basin- and Chicxulub-forming projectiles in the main-asteroid-belt size distribution[18,30]; see also http://www.lpl.arizona.edu/tekton/crater.html. The red boxes denote time intervals with constraints. For the lunar Late-Imbrian era (box 1; 3.2–3.7 Gyr ago), there are three such craters observed (Iridium, Humboldt, Tsiolkovskiy, with diameters of 260, 207 and 180 km, respectively), while for the Eratostenian era (box 2; 1.5–3.2 Gyr ago), there is one observed (Hausen, 167 km in diameter)[2,3]. Hausen might also be a Late Imbrian-era crater[31]. The remainder correspond to terrestrial impact spherule beds from specific Archaean and early Proterozoic terrains that have been extensively searched: at least seven beds between 3.23 and 3.47 Gyr ago (box 3), four beds between 2.49 and 2.63 Gyr ago (box 4), and one bed between 1.7 and 2.1 Gyr ago (box 5)[5–9]. The Chicxulub-sized craters Vredefort (2.02 Gyr ago) and Sudbury (1.85 Gyr ago) formed in box 5, so the true value should be 2 (ref. 3). No spherule beds have been found between 0.6 and 1.7 Gyr ago, but this time interval has not been extensively explored for impact spherules[6]. Over the same time intervals, our model results are essentially identical; for boxes 1 to 5, we obtain 3 ± 2, 1 ± 1, 9 ± 3, 3 ± 2 and 1 ± 1, respectively.

The E belt continued to produce large lunar impacts well after the conventional end of the LHB at 3.7–3.8 Gyr ago, with three roughly Chicxulub-sized or larger craters made on Late-Imbrian-era terrains (3.2–3.7 Gyr ago) and perhaps one on Eratostenian-era terrains (1.5–3.2 Gyr ago); see ref. 2 (http://ser.sese.asu.edu/GHM/) and ref. 3 (Fig. 3). These values match observations. In contrast, very few comparable-sized impacts are expected to come from ejected main-belt asteroids or comets over these times[13].

The ratio of the gravitational cross-sections of Earth and the Moon found using our E-belt encounter velocities is about 17:1. Thus, as predicted by our simulations, the existence of four Chicxulub-sized lunar craters younger than 3.7–3.8 Gyr implies that 68 ± 8 similar impacts should have taken place on Earth over a comparable formation period. These impact rates yield 9 ± 3, 3 ± 2, 1 ± 1 and 1 ± 1 events over 3.23–3.47, 2.49–2.63, 1.7–2.1 and 0.6–1.7 Gyr ago, respectively, enough to reproduce the known Archaean and early Proterozoic spherule bed data (Fig. 3b).

The largest Archaean-era blasts rivalled those that formed lunar basins during the Nectarian- and Early Imbrian eras. We calculate that 15 ± 4 basin-forming impactors struck Earth between 2.5 and 3.7 Gyr ago (Fig. 3a). Some may even have been as big as the one that formed the Orientale basin[4,5]. The terrestrial consequences of these mammoth Archaean events have yet to be explored, but we suspect that they may have affected the evolution of life and our biosphere in profound ways.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions W.F.B. developed the scenario of the E belt. The numerical runs were constructed by W.F.B. and D.V., with input from D.M., D.N. and H.F.L. Information on the initial conditions of the planets and the nature of late giant planet migration within the Nice model was provided by A.M., R.B., H.F.L. and D.N. Information on the nature of sweeping resonances, how they affected the main belt, and what happened afterwards was provided by D.M., A.M. and R.B. Additional numerical runs not shown here were performed by A.M. and R.B. Information on the nature of impact spherules and their context was provided by B.S. All authors participated in numerous discussions.

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