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High-velocity collisions from the lunar cataclysm recorded in asteroidal meteorites

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The Moon experienced an intense period of impacts about 4 Gyr ago. This cataclysm is thought to have affected the entire inner Solar System and has been constrained by the radiometric dating of lunar samples: ^{40}Ar–^{39}Ar ages reflect the heating and degassing of target rocks by large basin-forming impacts on the Moon. Radiometric dating of meteorites from Vesta and the H-chondrite parent body also shows numerous ^{40}Ar–^{39}Ar ages between 3.4 and 4.1 Gyr ago, despite a different dynamical context, where impacts typically occur at velocities too low to reset geochronometers. Here we interpret the ^{40}Ar–^{39}Ar age record in meteorites to reflect unusually high impact velocities exceeding 10 km s^{-1}. Compared with typical impact velocities for main-belt asteroids of about 5 km s^{-1}, these collisions would produce 100–1,000 times more highly heated material by volume. We propose that the ^{40}Ar–^{39}Ar ages between 3.4 and 4.1 Gyr ago from Vesta, the H-chondrite parent body and the Moon record impacts from numerous main-belt asteroids that were driven onto high-velocity and highly eccentric orbits by the effects of the late migration of the giant planets. We suggest that the bombardment persisted for many hundreds of millions of years and affected most inner Solar System bodies.

Impacts are a ubiquitous feature on planetary surfaces, responsible for heating the surface materials and disturbing or resetting their radiometric ages. Impact-reset lunar samples have been used to illuminate the bombardment history of the Moon, and by extension, that of the inner Solar System[1–5]. For example, early analyses of lunar nearside samples returned by the Apollo missions showed a clustering of impact-reset radiometric ages near 3.9 Gyr ago and a lack of older ages[6–8]. This suggested that an impact spike—the so-called lunar cataclysm or late heavy bombardment (LHB)—made many lunar basins and craters at this time. Subsequent identification of impact-reset ages before 4.0 Gyr ago in zircons and lunar breccias[9], combined with the interpretation that many 3.9 Gyr ages may be derived from one of the youngest and largest basins (Imbrium), however, has weakened support for a sharp LHB spike[10]. An endmember alternative is that ancient lunar ages represent impacts from a smoothly declining bombardment of leftover planetesimals (for example, ref. 11). Models of this scenario, however, have difficulty reproducing key LHB-era constraints, such as the formation of the large and young lunar basins Imbrium and Orientale[12–16].

To overcome this ambiguity, we turn to data representative of the impact history of main-belt asteroids. Impacts produce Ar loss if the target is heated for a long enough time beyond a threshold temperature[2]. Accordingly, high-heating collisions are the most likely events to be recorded. Here we explore the ^{40}Ar–^{39}Ar resetting age distributions found over the LHB era within two large meteorite classes: the howardite, eucrite and diogenite (HED) meteorites, whose source is probably the differentiated asteroid Vesta[17–20], and the high-metal H-type ordinary chondrites, whose ∼200-km-diameter parent body is unknown (hereafter HPB; for example, ref. 21). The parent bodies of each class are embedded in the main-asteroid belt, with their fragments delivered to Earth by a combination of collisions, non-gravitational forces, and resonances[22].

The ^{40}Ar–^{39}Ar age distribution of the eucrites and howardites (the diogenites contain so little K that they produce negligible radiogenic Ar) show three main features: a strong and narrow spike at ∼4.45 Gyr ago, which is mainly comprised of unbrecciated, cumulate and monomict eucrites[23]; few ages between 4.1 and 4.4 Gyr ago, found mainly in howardites, brecciated and polymict eucrites; and numerous ages between 3.4 and 4.1 Gyr ago, some of which were energetic enough to reset unbrecciated and cumulate eucrites at depth (Fig. 1 and Supplementary Fig. S1; and references therein). The fact that the 4.1–4.4 Gyr ago interval has ∼4–5 times fewer reset samples than the 3.4–4.1 Gyr ago interval suggests an increase in the impactor flux starting near 4.1 Gyr ago[1,5]. Interestingly, ancient H-chondrite ages show a similar ^{40}Ar–^{39}Ar age distribution (Fig. 1 and references therein). This implies that Vesta and the HPB experienced comparable impact histories. It must be noted that ^{40}Ar–^{39}Ar age distributions cannot be used to quantitatively estimate the impact flux on the respective parent bodies[2] (see also Supplementary Information); nevertheless, it is remarkable that lunar, HED and H-chondrite samples exhibit an uptick in the number of reset ages at about 4.1–4.2 Gyr ago.

HED and H-chondrite age distributions seem to contradict our present understanding of main-belt evolution. It is thought that the primordial main belt was at least several times its present mass for the first few hundreds of millions of years of its existence[24–27]. The extra material was then ejected onto planet-crossing orbits as

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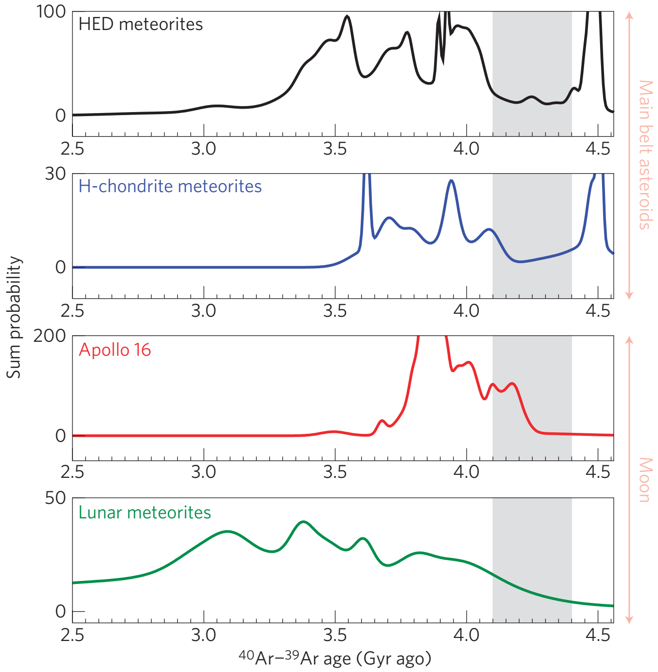

Figure 1 | Distributions of impact-reset ^{40}Ar–^{39}Ar ages of meteorites and lunar samples. Each curve represents the sum probability obtained by adding Gaussian profiles with centres and widths corresponding to the most probable age and $1-\sigma$ errors of each dated sample. The grey area between 4.1 and 4.4 Gyr ago is characterized by very few reset samples within the HEDs and H-chondrites. Data sources: HEDs (54 ages; refs 2,29 and references therein); H-chondrites (32 ages; ref. 3 and references therein); lunar samples (85 ages from Apollo 16 and 57 ages from lunar meteorites, see Supplementary Information).

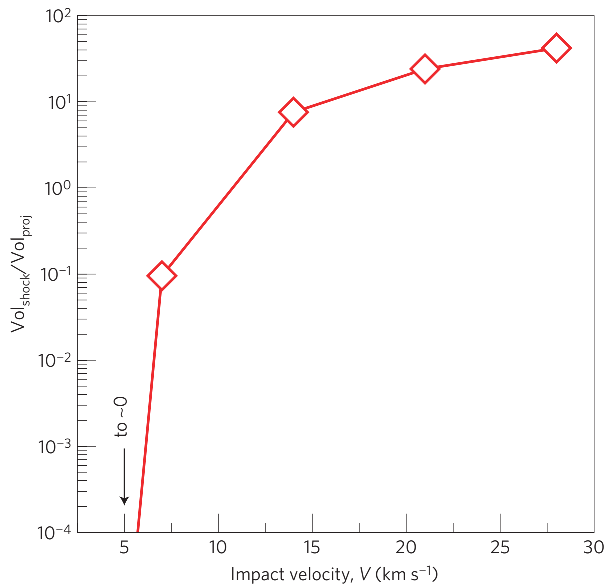

Figure 2 | Hydrocode-based computations of impact heating for various collision velocities. The runs were performed using the two-dimensional hydrocode iSALE (for example, refs 46,47). We simulated 10-km-diameter projectiles hitting Vesta vertically at velocity V_{sim} on a cylindrically symmetric computation grid. We then assumed V_{sim} was the vertical component of an impact velocity V hitting 45° from vertical (for example, $V = 14$ km s^{-1} corresponds to $V_{sim} = 10$ km s^{-1}). The y axis is the volume of shocked material (Vol_{shock}) reaching or exceeding 1,000 K over impactor volume (Vol_{proj}).

a consequence of a dynamical instability that triggered late giant planet migration, with resonances sweeping across the main-belt zone from the outside in[24,25]. Modelling work constrained by lunar and terrestrial data indicates that the timing of this last event was 4.1–4.2 Gyr ago[12,16]. Accordingly, we might expect Vesta and the HPB to have experienced numerous impacts between 4.1 and 4.4 Gyr ago, when the main belt was massive, and far fewer collisions after 4.1 Gyr ago, when the main belt was depleted of material. Instead, Fig. 1 shows the opposite.

Hydrocode simulations of impact heating on Vesta

To better interpret the ^{40}Ar–^{39}Ar age distributions of the HEDs, we performed a suite of impact simulations into Vesta at different velocities. We found that the peak temperatures and volumes of material heated above a given threshold (for example, the closure temperature for Ar loss, causing age reset) were strongly dependent on the impact velocity V. In particular, the estimated volume of shocked material raised above our reference temperature of 1,000 K was negligible for impacts at the average main-belt velocity of ~5 km s^{-1} (ref. 28), whereas it increased by many orders of magnitude for $V > 10$ km s^{-1} (Fig. 2 and see Supplementary Information). Moreover, velocities >10 km s^{-1} are needed to produce significant heating in the displaced material region (that is, the region between excavation and transient crater depths) or at greater depth. This is the region where the ages of cumulate and unbrecciated eucrites have probably been reset, to avoid later brecciation (see Supplementary Information). Therefore, if all other parameters remain the same, we predict that most of the ^{40}Ar–^{39}Ar ages in Fig. 1 were produced by high-velocity impactors.

We chose 1,000 K as a reference temperature that, while well below the melting temperature of silicates (~1,420 K), is in the regime where Ar diffuses rapidly from feldspar over timescales commensurate with impact-heating events[29,30], creating identifiable impact-reset Ar loss profiles. Selecting a modestly different threshold temperature should not affect our conclusions. Furthermore, the shape of our heating function shown in Fig. 2 is consistent with previous analytical works[31] and simulations of impact melt production[32,33].

Curiously, high-velocity impacts on Vesta are rare in the present main belt: <3% take place at $V > 10$ km s^{-1} (ref. 28; Supplementary Fig. S4). This probably explains the paucity of impact melt among HEDs (ref. 34) and why so little of it has been observed within Vestan craters[35], despite the numerous craters observed[36]. To reach $V > 10$ km s^{-1}, projectiles often need sizable inclinations, which are rare in the present main belt, and/or eccentricities larger than 0.5, which take them out of the main belt entirely and onto planet-crossing orbits. Such eccentric impactors, however, have dynamical lifetimes of only a few to a few tens of millions of years; most are readily eliminated by hitting the Sun, a planet, or being thrown out of the inner Solar System through an encounter with Jupiter (for example, refs 12,24). This leaves them little time to strike small targets such as main-belt asteroids.

Origin of lunar cataclysm-era high-velocity impactors

The short dynamical lifetimes of planet-crossing objects would seem to make them unlikely sources of numerous ^{40}Ar–^{39}Ar ages between ~3.4 and 4.1 Gyr ago. After all, a large population placed at one time onto such orbits would create a spike of ages only a few tens of millions of years long at best. A possible solution, however, may be found in new ideas of how main-belt asteroids evolved in the aftermath of late giant planet migration and resonance sweeping[24]. Here, numerous asteroids were ejected out of the main-belt region, but over timescales of many hundreds of millions of years.

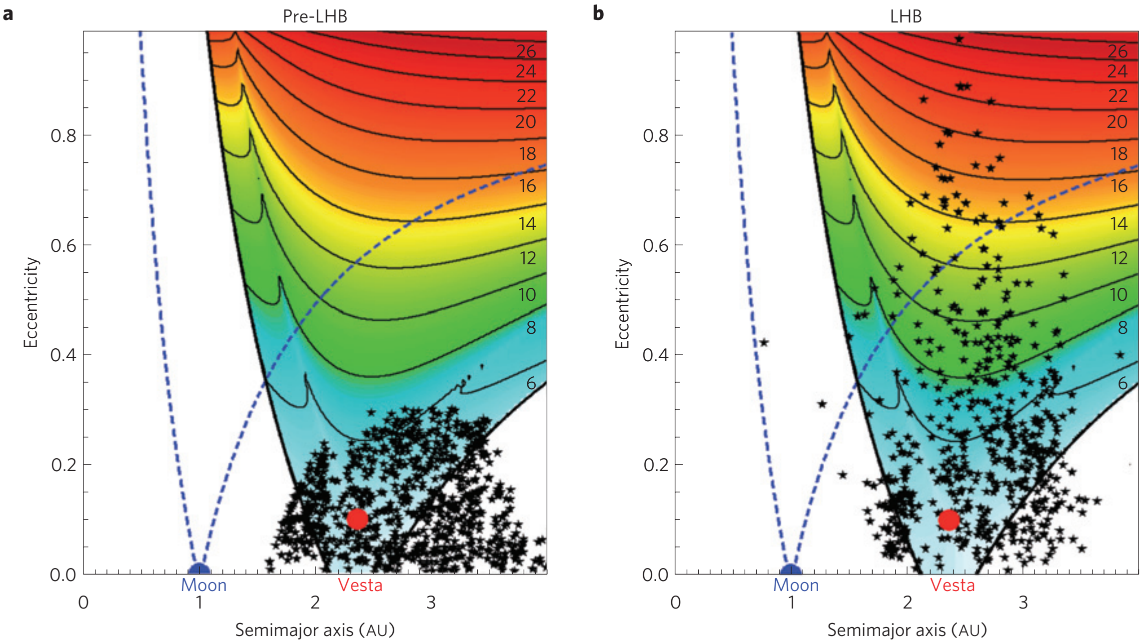

Figure 3 | The asteroid belt before and after late giant planet migration. a, The primordial main belt between 4.1 and 4.55 Gyr ago before the LHB (see Methods). Test asteroids are shown as black stars. The contours represent the mean impact velocities V (km s^{-1}) between projectiles with inclinations of 10° and Vesta (which is indicated by a red dot). Objects outside the contours cannot strike Vesta. Those between the blue dashed lines can hit the Earth and Moon. **b**, Our test asteroids 5 Myr after the giant planets have migrated to their present orbits. The most eccentric asteroids can hit Vesta and the Moon at high V (see Supplementary Fig. S4).

To explore this hypothesis, we tracked the impact flux of asteroids striking Vesta before and after the events of the so-called Nice model, a plausible scenario of late giant planet migration[12,24] (Fig. 3a). In this model, the giant planets are assumed to start on circular and nearly co-planar orbits between 5.4 and 11.7 AU, as determined by gas giant evolution models[24,37]. We assumed they kept these orbits between 4.1 and 4.55 Gyr ago. Into this system, test asteroids were placed on non-planet-crossing orbits between 1.7 and 3.5 AU, with all objects having eccentricity $e < 0.3$ and inclination $i < 20°$ (Fig. 3a); full initial conditions are described in refs 12,24; see also Methods. Then, at 4.1 Gyr ago, we assumed the gas giant planets experienced a dynamical instability, with planetary encounters driving them to their present orbits in less than 1 Myr (refs 24,25,37,38). This allowed their resonances to sweep across the main belt from the outside in, exciting the test asteroids and driving three-quarters of them onto planet-crossing orbits over timescales that varied from millions of years to many hundreds of millions of years (Fig. 3b and see Methods).

As our test asteroids evolved in this system, we used an Öpik-like algorithm from ref. 28 to compute the intrinsic collision probabilities and impact velocities between them and Vesta every 0.01 Myr. We terminated our simulation at 3.5 Gyr ago, when the orbits of the surviving test asteroids were reasonably similar to those of the present main belt. Note that the population of Earth/Moon-crossing asteroids generated as a result of the giant planet migration has been shown to fit the LHB-era lunar cratering record[16], the crater size-frequency distribution on ancient terrains[15,39] and terrestrial cratering constraints[12].

Our derived relative impact flux for Vesta, shown in Fig. 4a, shows that most impacts occurred between 4.1 and 4.55 Gyr ago. This is when the mass of the primordial asteroid belt was highest (see Methods). The mean impact velocities over this interval were ~4.7 km s^{-1}, with 0.2% of all projectiles hitting at $V > 10$ km s^{-1} (Fig. 3a). Resonance sweeping at ~4.1 Gyr ago then led to numerous main-belt asteroids being pushed onto planet-crossing orbits between 3.5 and 4.1 Gyr ago, where they were then eliminated. Although this led to a sharp decrease in the relative impact flux on Vesta, the fraction of asteroids hitting Vesta at $V > 10$ km s^{-1} increased to 11% (Fig. 3b).

Coupling these results with the relationships in Fig. 2, we find fairly limited impact heating on Vesta for the interval 4.1–4.55 Gyr ago but much more pronounced heating between 3.5 and 4.1 Gyr ago. This compares favourably to many aspects of the HED (and H-chondrites) data from Fig. 1. Moreover, the fact that howardite impact melts have ages between 3.3 and 4.0 Gyr ago (ref. 29) is a telltale sign of substantial heating from high-velocity projectiles during this time. Thus, the onset of late giant planet migration may explain why the HEDs (and H-chondrites) have multiple ^{40}Ar–^{39}Ar ages between 3.5 and 4.1 Gyr ago.

Most of the HEDs were probably ejected ~1 Gyr ago during the formation of the ~500-km-sized Rheasilvia basin on Vesta[35,36]. The fragments were placed into the Vesta family in the main belt, where they subsequently gave rise to precursors of HEDs on Earth-crossing orbits. If true, this suggests that the ^{40}Ar–^{39}Ar ages of the HEDs were probably reset in ancient craters that formed where Rheasilvia basin is located now. Our runs indicate that the Rheasilvia region, and probably the HPB, were struck at $V > 10$ km s^{-1} by 3–4 asteroids larger than 1 km diameter and by a few tens to a few hundreds of objects larger than 0.1 km diameter. This implies that the asteroid-derived ^{40}Ar–^{39}Ar ages in Fig. 1 represent the formation of craters smaller than a few tens of kilometres in diameter, in agreement with estimated crater sizes derived from cooling rates of specific meteorites[40,41].

Our model provides a rationale for why Rheasilvia's putative formation age was not sampled in the HEDs: the average impact velocity of main-belt projectiles striking Vesta today is ~5 km s^{-1}, low enough that only a few projectiles are likely to produce sufficient heating to trigger Ar loss. Moreover, we also expect reset material to be located where the heating takes place, namely within hot crater floors and/or ejecta blankets rather than in the escaping debris[2,40,42]. This behaviour also explains why the ^{40}Ar–^{39}Ar ages of stony meteorites differ from

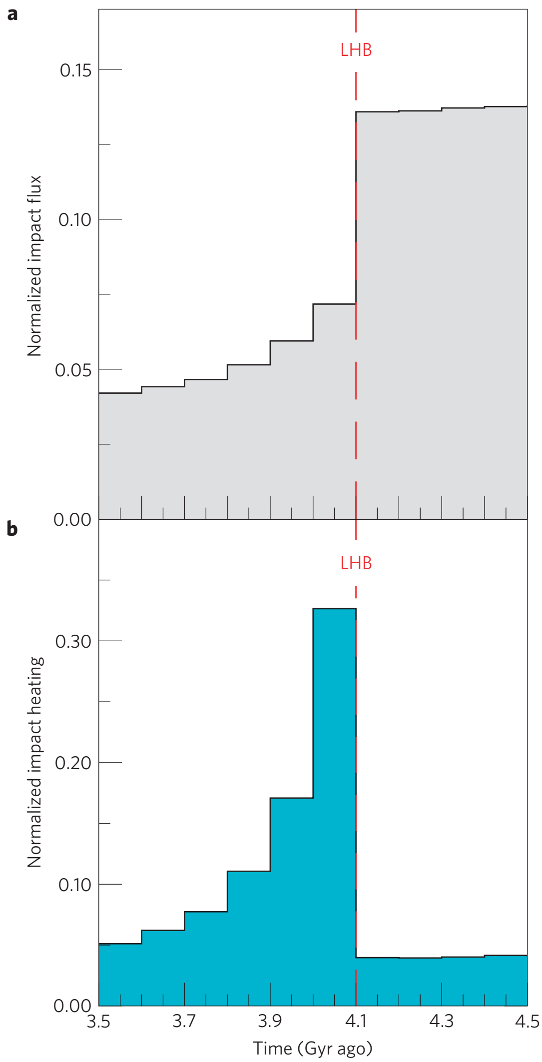

Figure 4 | The impact flux and impact heating curve on Vesta. The areas below the curves have been normalized to 1 (see Methods for other calculation details). **a**, Vesta's impact flux. Most impacts take place >4.1 Gyr ago when the primordial main belt's mass was highest. Giant planet migration ~4.1 Gyr ago (red dashed curve) drove sweeping resonances across the main belt population, depleting it and thereby decreasing Vesta's impact flux. **b**, The relative heating curve. Most heating takes place <4.1 Gyr ago because of an increased flux of $V > 10$ km s^{-1} asteroids striking Vesta from highly eccentric orbits.

their cosmic-ray exposure ages; the latter measure the time that metre-sized asteroids made by impacts have been free-floating in space[2,22,43].

The HED and H-chondrite ages in Fig. 1 do not show a decaying impact flux, as might be expected from model results (Fig. 4b). We believe that there are several reasons for this behaviour. First, the ^{40}Ar–^{39}Ar age distributions may sample only a modest number of events[1–3]. Therefore, low-number statistics should affect the overall shape of the age distributions. Second, recent impact-reset ages are more likely to be preserved on the surface than older ones; subsequent cratering and regolith formation/gardening should break apart and bury older samples, while leaving recent samples more accessible to a later ejection. We checked these ideas with the aid of a Monte Carlo terrain evolution code (see Supplementary Information). This work shows that the impact age distribution recorded on a given terrain may significantly differ from the impactor flux time-line.

Links between Vesta and lunar cataclysm impactors

The ^{40}Ar–^{39}Ar ages of impact melt clasts within lunar meteorites, which presumably were ejected from random locations on the lunar surface, and those from Apollo 16 rocks, which come from the ancient nearside lunar highlands, both seem to show an uptick in impact events near 4.1–4.2 Gyr ago, much like the HEDs and H-chondrites (Fig. 1). They are followed by a series of ^{40}Ar–^{39}Ar ages lasting hundreds of millions of years, although here the distributions are only modestly similar to the HEDs and H-chondrites. The fact that any similarity exists at all might be considered surprising; the Moon and main-belt asteroids not only have different dynamical contexts and bombardment histories, but the ^{40}Ar–^{39}Ar age sample sets in Fig. 1 measure larger impact events with their own particular selection biases[1,14]. The common thread is that the same projectiles resetting ^{40}Ar–^{39}Ar ages on Vesta and the HPB also have orbits that can strike the Moon at high velocities (Fig. 3b and Supplementary Fig. S4). This implies that ^{40}Ar–^{39}Ar ages derived from asteroid samples may allow us to glean new insights into the impact histories of both the Earth and Moon.

Another intriguing implication of this work concerns the ^{40}Ar–^{39}Ar events seen at ~4.5 Gyr ago among the HEDs and H-chondrites. Although some of those ages may reflect cooling through the blocking temperature after igneous crystallization, others are unambiguously related to early impact events during the planet formation era[2,3,41,44] (see also Supplementary Information). We postulate that these high-velocity impacts came from leftover planetesimals residing in the terrestrial planet region, many of which had highly eccentric and inclined orbits[13]. If true, these events from ~4.5 Gyr ago may constrain the nature and decay rate of this putative population as well as early planet formation processes.

Methods

The two snapshots shown in Fig. 3 show 810 test asteroids drawn from two dynamical runs. Those between 1.7 and 2.1 AU come from the lowest e Mars case from ref. 12, and those between 2.1 and 3.5 AU are from ref. 24. All have eccentricities $e < 0.3$ and inclinations $i < 20°$, with none on Mars-crossing orbits. Their mean i was set to 10° with $1-\sigma$ of 6°. The velocity contours were calculated using the methods found in ref. 28, where we calculated the mean impact velocities between an evenly spaced grid of bodies in semimajor axis a, e space, with $i = 10°$, and Vesta, which was given $(a, e, i) = (2.362$ AU, $0.0994, 6.35°)$ (ref. 45).

The impact flux on Vesta shown in Fig. 4a was calculated using test body runs from published works[12,24] as discussed in Fig. 3. They assumed that between 4.1 and 4.55 Gyr ago, the giant planets were on circular, nearly co-planar orbits between 5.4 and 11.7 AU. In ref. 24, 643 test bodies were given semimajor axis a values between 2.1 and 3.5 AU, whereas in ref. 12, 1,000 test bodies were placed between 1.7 and 2.1 AU. The two runs were combined, with the different test body results scaled so the asteroid belt was assumed to contain 0.8 and 3.1 times its preset population between 1.7–2.1 and 2.1–3.5 AU, respectively. Figure 3 shows a combination of these two sets of runs, with the test body numbers scaled in this manner for plotting purposes.

At 4.1 Gyr ago, the LHB was triggered when the giant planets migrated to their present orbits in less than 1 Myr. Between 3.5 and 4.1 Gyr ago, interactions with resonances drove 96% of 1.7–2.1 AU asteroids and 67% of the 2.1–3.5 AU asteroids onto planet-crossing orbits. The intrinsic collision probabilities (P_i) and impact velocity distributions (over 1 km s^{-1} bins) were calculated between our test bodies and Vesta every 0.01 Myr using the methods described in ref. 28. For reference, the mean P_i values for the 1.7–2.1 AU and 2.1–3.5 AU populations with Vesta between 4.1 and 4.55 Gyr ago were 4.5×10^{-18} and 3.54×10^{-18} km^{-2} yr^{-1}, respectively. The combined impact velocity distributions for 3.5–4.1 Gyr ago and 4.1–4.55 Gyr ago are shown in Supplementary Fig. S5. The relative heating flux (Fig. 4b) was calculated by applying the heating curve relationships (Fig. 2) to our velocity distributions and combining them using our collision probabilities. The combined impact velocity distributions for 3.5–4.1 Gyr ago and 4.1–4.55 Gyr ago are shown in Supplementary Fig. S5.

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Author contributions

S.M. and W.F.B. performed much of the numerical modelling work. K.W. performed the hydrocode simulations used to generate the impact heating relationships. Compilations of the Ar–Ar data, as well as a detailed analysis of how these age distributions should be interpreted, were provided by B.A.C., D.A.K., M.C.D.S. and S.M. All authors contributed to a discussion of the results and their implications.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.M.

Competing financial interests

The authors declare no competing financial interests.

CORRIGENDUM

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In the print version of this Article, in the 7th author affiliation the US state is incorrect; it should read 'Arizona'. The 'accepted' date of the Article is also incorrect; it should read 8 February 2013. These errors are correct in the HTML and PDF versions.