RECONCILING ASTEROID COLLISION AGES WITH THE LATE HEAVY BOMBARDMENT. W. F. Bottke[1], S. Marchi[1], D. Vokrouhlický[1,2], B. A. Cohen[1,3], *(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) NASA Marshall Space Flight Center, Huntsville, AL.*

Introduction. The Late Heavy Bombardment (LHB) was a solar system-wide barrage of comets and asteroids that produced many young lunar basins, with the last one Orientale formed $\sim$ 3.7-3.8 Ga [e.g., 1]. The precise nature of the LHB, however, is uncertain; some believe it represents the end of a steadily-declining bombardment due to leftover planetesimals, while others believe it was a "cataclysm" marked by increased lunar impact rates ~ 4.0 Ga. How do we distinguish between these two different scenarios of solar system history?

One way is to examine asteroid and lunar samples that were strongly heated by LHB-era impact events. Interestingly, the ancient ^{39}Ar-^{40}Ar shock degassing age profiles from HEDs, presumably from (4) Vesta, the H chondrites, and ancient lunar rocks returned by the Apollo 16 and Luna 20 missions are surprisingly similar to one another [2-6]. The asteroids yield a spike of ages near 4.5 Ga, few ages between $\sim$ 4.1-4.4 Ga, and numerous ages between $\sim$ 3.5-4.1 Ga [2-4]. The Moon yields few Ar-Ar ages older than 4.1-4.2 Ga and numerous ages between 3.7-4.1 Ga [2, 5-6].

Interpreting the LHB. These age distributions may suggest the LHB began $\sim$ 4.1-4.2 Ga. This partially supports the cataclysm scenario, though impacts prior to 4.1-4.2 could still come from the leftovers of accretion. A likely trigger was late giant planet migration (Nice model) that destabilized the primordial main belt and numerous other small body reservoirs [e.g., 7].

The age range between 3.5-4.1 Ga also implies the LHB was not a spike, but instead lasted hundreds of My. This means the main source of LHB-era impactors was probably asteroids, not comets; the Nice model predicts comets hit inner solar system targets over a few tens of My at best, while asteroids produce impacts over much longer time periods [8]. A probable source of many LHB-era impacts is the E-belt, a putative main belt extension between 1.8-2.1 AU that was eliminated by late giant planet migration. Numerical work shows this population made most Nectarian and Imbrian-era lunar basins between 3.7-4.1 Ga [8].

LHB Problems. The catch, however, is that we still need explain the paucity of Ar-Ar ages between 4.1-4.4 Ga. Most pre-Nectarian craters formed in this interval [10], and the primordial main belt was several times its current size [8,9], such that Vesta impacts should have been common. This is the opposite of observations.

One possibility is that early impacts obliterated or buried most older samples. While this certainly happens at some level, we do not believe it explains observations: (i) pre-4.1 Ga crystallization and igneous ages of asteroid and lunar samples have been found in some abundance [2-6], (ii) extensive destruction of older terrains on Vesta/Moon is not obvious from crater counts [10], and (iii) obliteration/burial should presumably work differently on the worlds above, which vary in size and situation, yet the Ar-Ar age profiles for the Moon, Vesta, and the H chondrite parent body are broadly similar.

LHB Impact Heating Model. We argue the missing factor here is a realistic model of how impact heating really works. Hydrocode simulations show that the amount of melt/vapor produced at $V > 15$ km/s scales with impactor energy [11-14]. For $V < 15$ km/s, however, the zone of melting drops off quickly as the peak shock pressure achieved in an impact approaches the peak pressure for melting. In fact, tests show the volume of vapor/melt decreases by factors of 10 and 100 from $V = 15$ to 10 km/s and to 7-8 km/s, respectively [14].

This means low V impacts do not heat the target sufficiently to reset Ar-Ar ages. **Consequently, no matter how massive the main belt was before/after the LHB, it cannot produce much heating because mean impact velocities there were likely 5 km/s [15].**

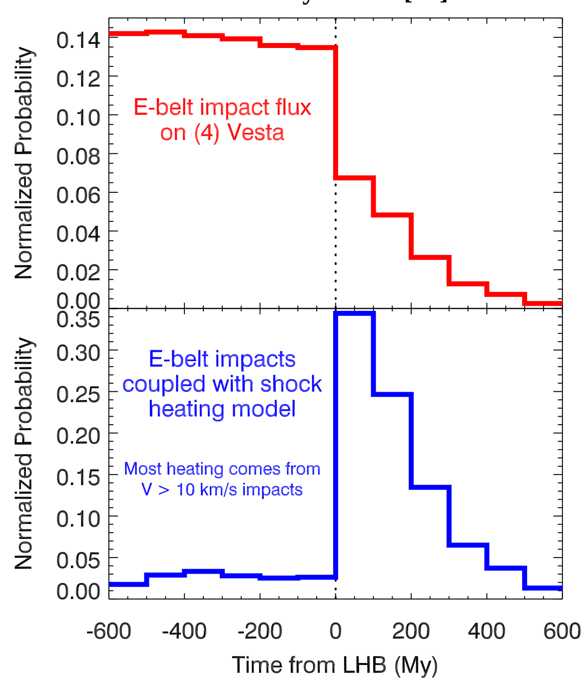

Fig. 1. *(a) The normalized impact flux on Vesta from the E-belt. Most impacts occur prior to LHB. (b) Flux coupled to impact heating scaling relationships.*

Using this data, we calculated the normalized amount of impact heating that takes place on the Moon and Vesta from the impact of E-belt asteroids before/after the LHB. First, we calculated the orbital evolution of E-belt objects [8]. We neglected the primordial main belt, but this should not affect our conclusions. In the *pre-LHB phase*, Venus-Neptune were placed on nearly circular orbits consistent with Nice model initial conditions. Our 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 moved all planets to their current orbits. The surviving test bodies were tracked for 0.6 Gy. Next, we calculated the collision probability and impact velocity distributions of our bodies with Vesta and the Moon using [15]. The results were then coupled to impact heating scaling relationships valid for our targets [11-14].

Vesta Results. *Fig. 1* shows our results for E-belt impacts on Vesta. Most pre-LHB collisions are too slow to produce significant heating, explaining the paucity of 4.1-4.4 Ga ages in the HEDs (and H chondrites). Those pre-LHB events that do occur are mainly from E-belt escapees that achieve high eccentricity e and/or inclination i orbits. Many cross the orbits of both Vesta and the Moon as they evolve, such that they occasionally hit either world at $V >$ 10-15 km/s.

During the LHB, most E-belt asteroids are driven onto planet-crossing orbits, which in turn creates numerous high V impacts on Vesta. This explains why the HED (and H chondrites) have multiple Ar-Ar ages between 3.5-4.1 Ga. As the population decays, the number of impact heating events also decreases, though this is partially offset by selection effects that favor recent events. Together, they help keep the observed Ar-Ar age distributions relatively flat.

Lunar Results. Here we scale our numerical results to compare the pre-LHB and LHB eras. For the LHB, destabilized bodies from the E-belt and primordial main belt produce $\sim$ 12 lunar basins, or most Nectarian and Imbrian-era basins [8]. For the pre-LHB flux, most impacts probably come from a combination of leftover planetesimals in the terrestrial planet regions and escapees from the primordial E- and main belts. Unfortunately, we do not yet have a good model of the former, particularly because the giant planets may have formed on nearly-circular and co-planar orbits [7].

As an approximation, we scaled the E-belt impactor flux in the pre-LHB era to the observed fraction of pre-Nectarian basins, which make up two-thirds of all lunar basins [1]. We believe this is reasonable because (i) the mean lunar V of E-belt impactors doubled between the pre-LHB and LHB eras (11.9 ± 8.1 km/s vs. $V = 20.7 \pm 9.8$ km/s, respectively [8]), and (ii) the differences between the crater size-frequency distributions on the oldest pre-Nectarian terrains and those near Nectaris basin are most easily explained by a factor of 2 increase in V near the time of the LHB [10].

Fig. 2 shows that while LHB projectiles only produce 1/3 of all lunar basins, they create more than half of all Ar-Ar ages over an interval lasting several hundreds of My. Selection effects should bias these values even more toward LHB-era events; we note that the nearside regions sampled by Apollo 16 (lunar highlands) and Luna 20 (near Crisium basin) are closer to Nectarian-era basins than pre-Nectarian-era basins. Thus, our results appear consistent with constraints.

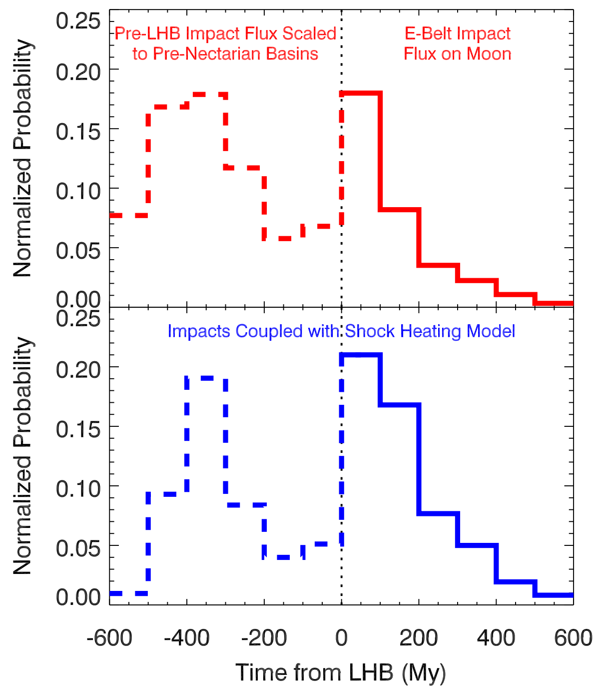

Fig. 2. *(a) Impact flux on Moon. To approximate leftover planetesimal impacts prior to LHB, we scaled E-belt impact flux in the pre-LHB era to pre-Nectarian basin counts, which make up 2/3 of all lunar basins. (b) Flux coupled to impact heating scaling relationships.*

Implications. The LHB-era Ar-Ar shock degassing ages from (4) Vesta, the H chondrite parent body, and the Moon have similar profiles because these worlds were hit by the same population of high (e, i) impactors; only these kinds of high V impactors can produce significant heating. We predict that the age profiles of lunar impact spherules [16], impact melt clasts from lunar meteorites [17], and the $<$ 1.3 Ga Ar-Ar ages found among H chondrites [4] are broadly similar for the same reason.

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