THE E-BELT: A POSSIBLE MISSING LINK IN THE LATE HEAVY BOMBARDMENT. W. F. Bottke[1], D. Vokrouhlický[2], D. Nesvorný[1], D. Minton[1], A. Morbidelli[3], R. Brasser[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) Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, B.P. 4229, 06304 Nice Cedex 4, France*.

Motivating Problem. The Late Heavy Bombardment (LHB) is defined as a period 3.96-3.75 Ga when many lunar basins (e.g., Serenitatis, Imbrium) and impact melts were produced [1]. The primary source of the bombardment is unknown, though some argue it was the primordial asteroid belt between 2.1-3.3 AU; the size-frequency distribution (SFD) of main belt asteroids and that of ancient lunar craters are surprisingly similar [2], and the LHB may last longer than is sustainable from a comet disk in the outer solar system [3]. With this said, however, the primordial main belt is not without its issues.

For example, based on what we know of the main belt, one would predict that typical LHB impactors should resemble common asteroids and meteorites (i.e., S/C-types, many which may be like ordinary and carbonaceous chondrites). Instead, studies of highly siderophile elements (HSE) in ancient lunar impact melts (> 3.8 Ga) show that LHB impactors were surprisingly exotic; the closest matches were to thermally-evolved objects that are uncommon in the current main belt (e.g., enstatite chondrites, iron meteorites, and/or differentiated meteorites) [4,5]. Comparable results come from terrestrial samples; HSE studies suggest the extraterrestrial material mixed into Earth's primitive mantle after the Moon-forming impact (i.e., Earth's late veneer) was dominated by enstatite chondrite-like projectiles [6].

As a second example, we cite the apparent contradiction that exists between the predicted size of the main belt needed to produce the LHB (i.e., 10-40 times the current SFD; [3]) and new dynamical results that indicate the main belt only lost 2-3 times its population [7,8]. If the latter results are valid, the main belt had insufficient mass to produce much of the LHB.

Possible Solution. With these ideas in mind, we decided to reexamine the evolution of the inner solar system. In somewhat broad strokes, we believe the following items are true.

Item 1. The ν_6 secular resonance, produced by the current configuration of the giant planets, defines the inner edge of the main belt at ~ 2.2 AU. The region between Mars and the ν_6 resonance today is largely unstable (though see below). If giant planet migration drove the LHB, however, the ν_6 resonance was in a different place before the LHB [3,7]. This implies that the primordial main belt did not stop at 2.2 AU; our numerical tests indicate that stable zones may have existed all the way down to the primordial orbit of Mars.

Item 2. Numerical studies suggest the parent bodies of the LHB impactors likely formed near/in the terrestrial planet region, where fast accretion times allowed planetesimals to heat up/melt early in Solar System history by the decay of short-lived radionuclides [9]. Planet formation processes scattered some of the remnants outward, allowing a lucky few to reach stable dynamical zones beyond Mars. We find it probable that more of this material reached the putative stable regions described in Item 1 than reached the asteroid belt.

Item 3. The Hungaria asteroids, a tiny population located at high inclinations between 1.8-2.0 AU, appears to have many objects that are spectrally similar to the LHB projectiles described above (e.g., E-types) [10]. Because it is the closest surviving reservoir of small bodies to the terrestrial planet region, it may tell us about the nature of the objects that once resided there.

Thus, given items 1-3, as well as the limitations of the proposed asteroidal and comet LHB source populations, we hypothesize that the inner main belt once had a stable extension that stretched toward Mars that was largely filled with the leftover planetesimals of terrestrial planet formation. We call this putative extinct population the *E-belt*. When the gas giants migrated to their current orbits during the LHB [3], we speculate that the E-belt was dynamically eliminated, the Hungarias were populated, and many objects went on to strike the Moon and terrestrial planets.

Testing the E-belt Hypothesis. It is not easy to test the E-belt hypothesis. Not only are our planet formation and late giant planet migration models incomplete, but the nature of the LHB as a cataclysm or a declining bombardment is still hotly debated [e.g., 1]. Furthermore, the hypothetical E-belt population could conceivably be given nearly any property that helps it pass a particular trial. For these reasons, our immediate goals are "quick and dirty" tests to see what works to reproduce LHB constraints and what doesn't. In the end, a good LHB model of the inner solar system should: (1) Produce a reasonable impact profile of lunar basins and craters; (2) Explain the preponderance of "exotic" LHB projectile types on the Moon (and Earth); (3) Create or explain the Hungaria asteroids; (4) Match LHB era constraints (e.g., Moon, Mars, main belt, outer solar system); (5) Be self-consistent with the best available planet formation and LHB-era evolution models.

Results. For space reasons, the runs described here only include our tests assuming a *strong* version of the lunar cataclysm [1,11,12]. We assumed the LHB was triggered by giant planet migration at 3.96 Ga [3], and that all observed lunar basins formed between 3.96-3.75 Ga [11,12]. According to our numerical tests, this implies Mars had a low eccentricity prior to the LHB; we find a standard Mars drives many asteroids out of the inner main belt and E-belt populations and would produce numerous observable lunar basins prior to 3.96 Ga. Instead, we assumed that giant planet migration excited Mars to larger eccentricities [13]. We integrated nearly 4000 test bodies with $a = 1.6$-2.1 AU, $e = 0$-0.3, and $i = 0°$-$15°$ within our current system of planets (Venus-Neptune) using `swift-rmvs3`. **Fig. 1** shows our initial conditions as well as a snapshot of what happens within one E-belt run after 50 My of evolution.

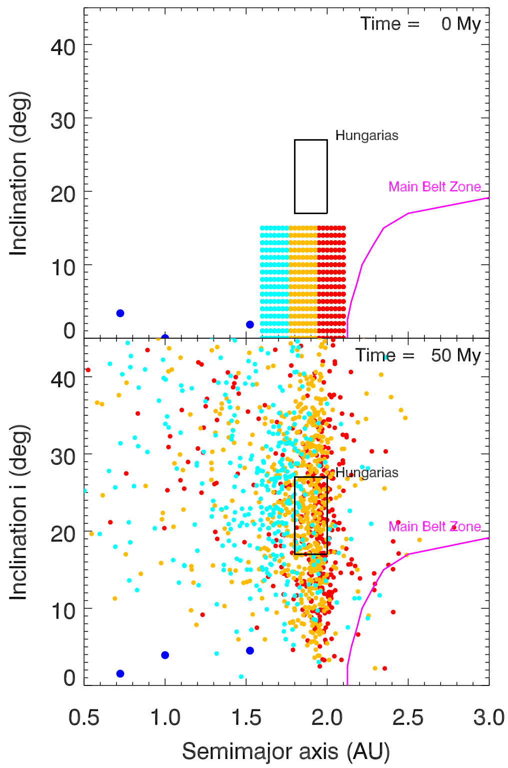

Figure 1. *Snapshots from our E-Belt runs. The bottom plot shows the E-belt particles at 50 My within a run where Mars' eccentricity has been excited ($e_{\rm MAX} \sim 0.23$) and inserted into a system with Venus-Neptune on standard orbits.*

In this run (and in all our E-belt runs), we found the impact probabilities between the Earth/Moon and E-belt bodies were 3-10 times larger than typical inner main belt values, with the highest values coming from asteroids orbiting close to Mars. These results imply the E-belt needs far less mass to produce the LHB than the main belt, particularly if its initial mass distribution increased toward Mars. The downside of this run, however, was that our impact profile produced too many late basin-forming events, mainly because E-belt objects between 1.7-2.0 AU found their way onto long-term stable orbits near the Hungaria region (Fig. 1).

It is difficult to removing excited, long-lived objects from the vicinity of the Hungaria region; many mechanisms in our tool-kit (e.g., sweeping resonances) tend to drive test bodies deeper into the stable zone, thereby preventing us from eliminating late lunar basin-forming events. Better results were found by increasing the eccentricity of Mars, which appears better suited at digging out these objects. Using our same E-belt initial conditions, we tested Mars orbits that could reach maximum eccentricities of $e_{\rm MAX} = 0.17, 0.2$, and 0.23. The latter runs produced the best lunar impact profiles, though all three produced some long-lived Hungarias with numbers/orbits consistent with observations.

Fig. 2 shows our best results to date using the $e_{\rm MAX} = 0.23$ run. Its impact profile matches lunar constraints, with most impactors come from 1.6-1.8 AU region, potentially explaining the exotic nature of the LHB projectiles. To make the LHB, this E-belt would need to be 5-6 times the size of the current main belt SFD, with much of the mass near Mars.

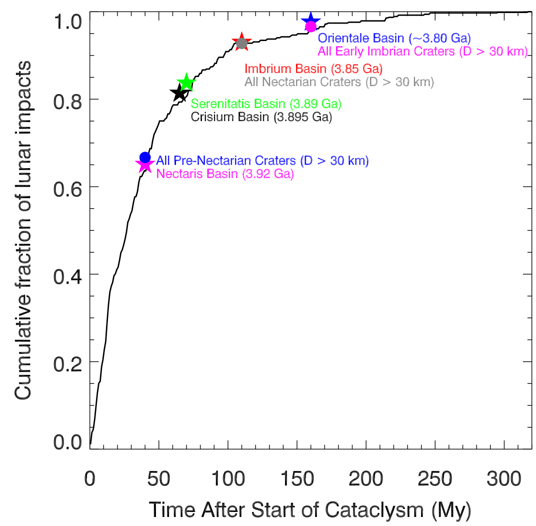

Figure 2. *The E-belt impact profile for the Moon where $e_{\rm MAX}$ for Mars was set to 0.23. For testing purposes, we assume a strong form of the lunar cataclysm that started at 3.96 Ga. The y-axis was created using the superposition sequence of the 43 known lunar basins from [14]. Basin age data was compiled in [1]. Crater data comes from [14].*

Caveats. While our tests indicate some promising directions, we still have a long way to go. For example, while the Fig. 2 run may pass tests 1-3, 4-5 have yet to be checked, and we are still working on the dynamical process that allows $e_{\rm MAX}$ for Mars to decrease from 0.23 to 0.12. Stay tuned.

References. [1] Stöffler & Ryder (2001) *Space Science Reviews* **96**, 9. [2] Strom *et al.* (2005) *Science* **309**, 1847. [3] Gomes *et al.* (2005) *Nature* **435**, 466. [4] Kring & Cohen (2002) *JGR-PL* **107** 5009. [5] Puchtel *et al.* (2008), *GCA* **72**, 3022. [6] Becker *et al.* (2006) *GCA* **70**, 4528. [7] Minton & Malhotra (2009) *Nature* **457**, 1109. [8] Morbidelli *et al.* (2009) BAAS 41, #55.03. [9] Bottke *et al.* (2006) *Nature* **439**, 821. [10] Warner *et al.* (2009) *Icarus* **204**, 172. [11] Tera *et al.* (1974) *EPSL* **22**, 1. [12] Ryder *et al.* (2000) *Origin of Earth & Moon* (U. Arizona Press), 475. [13] Brasser *et al.* (2009), *A & A* **507**, 1053. [14] Wilhelms (1987) *U.S. Geol. Surv. Prof. Pap. 1348*, 302 pp.