UNDERSTANDING THE IMPACT FLUX ON THE MOON OVER THE LAST 4.6 GY. W. F. Bottke[1], H. Levison[1], & A. Morbidelli[2]. [1]Southwest Research Institute, 1050 Walnut St, Suite 400, Boulder, CO 80302, USA (bottke@boulder.swri.edu). [2]Obs. de la Côte d'Azur, B.P. 4229, 06034 Nice Cedex 4, France

Introduction. Asteroids and comets have been bombarding the terrestrial planets since they formed almost 4.6 Ga. The impact flux over Solar System history, however, has seen considerable variation and is directly tied to the events that drove the planets to their current orbital configuration. We find it useful to divide the impact history of the terrestrial planet region into several stages: (i) the post-planet formation era (4.6-4.0 Ga), the late heavy bombardment (LHB) era (4.0-3.8 Ga), the post-LHB era (3.8 Ga-3.2 Ga) and (iv) the current era (3.2 Ga-Today).

Stage 1. The post-planet formation era (4.6-4.0 Ga). The earliest bombardment history of the Moon is a record of events that took place after the Moon-forming event and the solidification of the lunar crust (i.e., ~100 My after CAI formation). Little is known about the impact flux that occurred during this time. Using insights from planet formation models [e.g., 1], we can postulate different impact scenarios for this era: (a) A large swarm of planetesimals survived planet formation and proceeded to steadily pummel the terrestrial planets and Moon for 500-600 My; the heavily-cratered lunar highlands were presumably produced by these putative impactors. (b) Few planetesimals survived accretion. If so, the impact flux would have been dominated by refugees from the asteroid belt and "primordial" comet disk regions. If few of these objects escaped, or their size-distributions were very different from those currently observed, the impact flux for 500-600 My may have been limited (e.g., [2]).

Note that some crater-age chronologies assume scenario (a) is valid [3]. Using numerical simulations, we find that the post-accretion planetesimal population decays too rapidly to explain the formation of large lunar basins like Imbrium, Orientale, Serenitatis, and Crisium [4] (**Fig. 1**). These results, when combined with evidence of limited impacts during this epoch from terrestrial zircons [5], implies that the terrestrial impact flux during this stage was surprisingly low.

Stage 2. The LHB era (4.0-3.8 Ga). Recent numerical modeling work of the primordial evolution of the Solar System supports the view that the LHB is an impact spike [6, 7]. According to [6], the giant planets initially had orbits that were circular and much closer to each other (5 < *a* < 15 AU). In particular, the ratio of orbital periods of Saturn and Jupiter was smaller than 2, while it is almost 2.5 at present. This crowded region was surrounded by a massive disk of

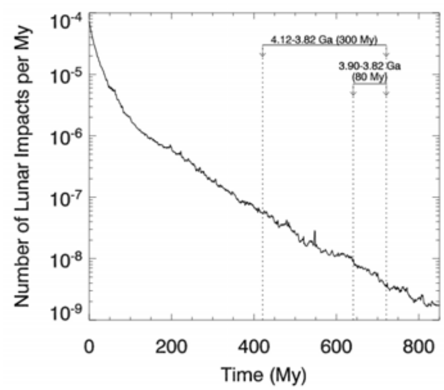

Fig. 1. The number of lunar impacts per My produced by a post-planet formation population (PPP). Lunar constraints indicate 2 and 4 D > 60 km basin-forming impactors struck between 3.90-3.82 Ga and 4.12-3.82 Ga, respectively. For the PPP to produce these impactors, it would need to have at least 1-10 Earth masses of material, exceeding Solar Nebula estimates

planetesimals of about 35 Earth masses; this was the forerunner of the current Kuiper belt and scattered disk. Dynamical interactions of the planets with this disk caused a slow increase of the orbital separation of planets. After 500-600 My, the ratio of orbital periods of Saturn and Jupiter became exactly equal to 2. This orbital resonance excited the eccentricities of these two planets which, in turn, destabilized the planetary system as a whole. The planetary orbits became chaotic and started to approach each other, which produced a short phase of encounters. Consequently, Uranus and Neptune were scattered outward into the disk, which destabilized it and abruptly increased the migration rates of the planets.

During this fast migration phase, the eccentricities and inclinations of the planets decreased via dynamical friction exerted by the planetesimals, allowing the planetary system to stabilize on their current orbits. At the same time, a huge flux of planetesimals reached the orbits or the terrestrial planets, from both the asteroid belt and the original trans-Neptunian disk [7]. Simulations show that $\propto 10^{22}$g of planetesimals hit the Moon during a ~100-200 My interval. This "terminal cataclysm" is consistent with the magnitude and duration of the LHB inferred from lunar craters [4, 7].

This model is consistent with additional lunar crater studies that argued that (i) asteroids dominated the LHB, (ii) asteroids were ejected from the asteroid belt by a size-independent process (presumably a resonance sweeping due to the migration of Jupiter and Saturn) and (iii) the total asteroid mass was insufficient to cause such a migration [8]. Moreover, the wave-like shape of the main belt size distribution at this time [9] matches the shape of the crater size distribution found on the lunar highlands.

Stage 3. The Post-LHB Era (3.8-3.2 Ga). Crater counts of Apollo-sampled terrains indicate that the lunar impact flux declined by a factor of ~5 between 3.8-3.2 Ga [e.g., 2, 3]. The source of this very gradual decline over 500-600 My is unknown, but we hypothesize it was produced by small body populations placed onto marginally unstable orbits during Stage 2 [10].

In Stage 2, resonances are forced to move into new locations by Jovian planet migration; this causes some to sweep across the asteroid belt and drive off ~90% of the indigenous population [7]. Some refugees, however, are placed onto orbits that are unstable over very long time periods (hundreds of My on average). At the same time, comets and asteroids forced out of their source locations can become trapped inside or near the periphery of the asteroid belt. This implies that a large population of comet-like bodies may have been captured at the time of the LHB in the outer main belt [10].

As those asteroids and comets placed onto long-term unstable orbits dynamically escape via planetary perturbations into the terrestrial planet region, they bombard the Moon and other planets. Accordingly, the lunar cratering record from the late Imbrium period constrains events from Stage 2. Comparable craters records on other bodies (e.g., Mercury, Mars) add to this picture.

Stage 4. The Current Era (3.8 Ga-Today). The lunar impact flux over the last 3 Gy has been relatively constant except for occasional changes possibly related to asteroid breakup events [3]. Most impactors on the terrestrial planets in Stage 4 are now thought to have been asteroids that were driven out of the main belt through a combination of collisions, non-gravitational (Yarkovsky) thermal drift forces, and resonances (e.g., [11, 12]). The asteroids reaching the planet-crossing region are the end-products of a collisional cascade process, such that the shape of the size distribution is near equilibrium [9]. This explains why the NEO size distribution is a near reflection of the main belt's wavy-shaped size distribution (**Fig. 2**; see also [13]).

Asteroids provide more than 90% of the near-Earth object (NEO) and Mars-crossing asteroid populations located at $a < 7.4$ AU [12]. The rest come from Jupiter-family comets, who likely account for less than 10% of the remaining population. The contribution from Long-period and Halley-type comets to the lunar impact flux

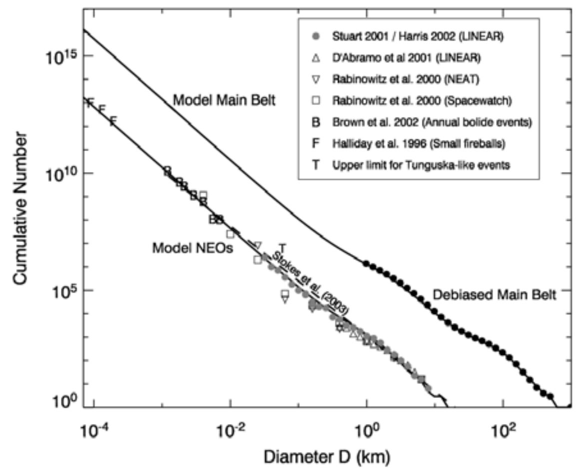

Fig. 2. The present-day main belt and NEA populations based on our model runs (solid lines). The shape of the NEA population is a reflection of the main belt, where Yarkovsky thermal drag causes $D < 40$ km asteroids to drift into resonances that in turn deliver them to the NEA population.

is only likely to be 4-5% of the total crater rate (which may increase by a factor of ~3 during putative comet showers).

Short-term deviations in this population may be caused by stochastic break up events. For example, the formation of the Baptistina asteroid family 160 My ago in the inner main belt [14] may have increased the NEO flux by a factor of 2-3 or so for ~100 My. We consider it likely that other major asteroid breakup events over the past 3 Gy (e.g., Flora [15]) have similarly influenced the lunar impact flux.

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