THE ASTEROID AND COMET IMPACT FLUX IN THE TERRESTRIAL PLANET REGION: A BRIEF HISTORY OF THE LAST 4.6 GY.

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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. To make sense of this history, we have divided the impact history of the terrestrial planet region into 3 broad stages: (i) the post-planet formation era (4.6-4.0 Ga), the late heavy bombardment (LHB) era (4.0-3.8 Ga), and (iii) the current era (3.8 Ga-today). Each is discussed below.

Stage 1. The post-planet formation era (4.6-4.0 Ga). We assume this stage starts after the Moon-forming impact (i.e., ~30 My after the formation of the first solids). Little is known about the impact flux that occurred during this time in Solar System history. Existing planetary formation models, while providing many useful insights, have yet to reproduce the orbital distribution of the planets [e.g., 1]. These ambiguities have led to two plausible impact scenarios for this era: (a) a large swarm of planetesimals survived planet formation and proceeded to steadily pummel the terrestrial planets for 500-600 My; the heavily-cratered lunar highlands were presumably produced by these putative impactors, and (b) few planetesimals survived accretion, such the impact flux on the terrestrial planets was limited for 500-600 My (e.g., [2]). Note that nearly all current 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 the lunar basins (e.g., at least 12 lunar impactors with masses 2×10^{19}g and 2 with masses 2×10^{19}g; [4]) over a timespan of 80-300 My near 4.1-3.8 Ga (**Fig. 1**). These results, when combined with evidence of limited impacts during this epoch from terrestrial zircons [5], imply that the terrestrial impact flux during this stage was surprisingly low.

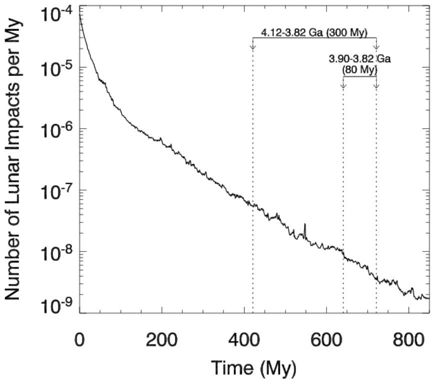

Fig. 1. The number of lunar impacts per My produced by a post-planet formation population (PPP). Lunar constraints indicate two D > 80 km basin-forming impactors either struck between 4.21-3.82 Ga or 3.90-3.82 Ga. For the PPP to produce these impactors, it would need to have at least 1-10 Earth masses of material, exceeding Solar Nebula estimates

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 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 bombardment" is consistent with the magnitude and duration of the LHB inferred from lunar craters [4, 7].

Interestingly, 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 current era (3.8 Ga-today). The impact flux on the terrestrial planets over the last several Gy has been dominated by asteroids driven out of the main belt through a combination of collisions, non- gravitational (Yarkovsky) thermal drift forces, and resonances (e.g., [10]). These bodies provide more than 90% of the near-Earth object (NEO) and Mars-crossing asteroid populations located at a < 7.4 AU [11]. The rest come from Jupiter-family comets, who likely account for less than 10% of the remaining population. Long-period and Halley-type comets were not explicitly accounted for by [11], but we estimate their contribution to the impact flux to be 4-5% of the total crater rate on Earth (which may increase by a factor of ~3 during putative comet showers).

Evidence from the lunar and terrestrial crater record suggests that the impact flux from this population has been relatively constant (within a factor of 2) from 0.5-0.8 to 3 Ga [e.g., 12]. This result is readily explained using asteroid collisional evolution and delivery models [9]; they show that the main belt population has reached a quasi-steady state, with collisional breakup events both eliminating existing bodies and producing new fragments. The asteroids reaching the planet-crossing region are the end-products of a collisional cascade. 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]). Short-term deviations in this population may be caused by stochastic break up events. It is plausible that the formation of the Flora family 500 My ago [14] increased the NEO flux by a factor of 2 or so.

So far, little evidence has been found in main belt and planet-crossing asteroid observational/modeling work for a population of bodies capable of explaining the steep size distribution of sub-km craters observed on the Moon and Mars (e.g., differential power law index -4.8) [15]. For example, as described by [16], crater saturation models used to analyze the crater histories of Gaspra, Ida, Mathilde, and Eros yield results that are most consistent with a time-averaged population that has differential power law indices of q_a = -3.5 for $D < 0.2$ km and q_b = -2.6 for 0.2 km < D < several km (Fig. 2). Based on this, we believe the most plausible explanation for these craters is that they are secondary impacts generated by ejecta from large craters.

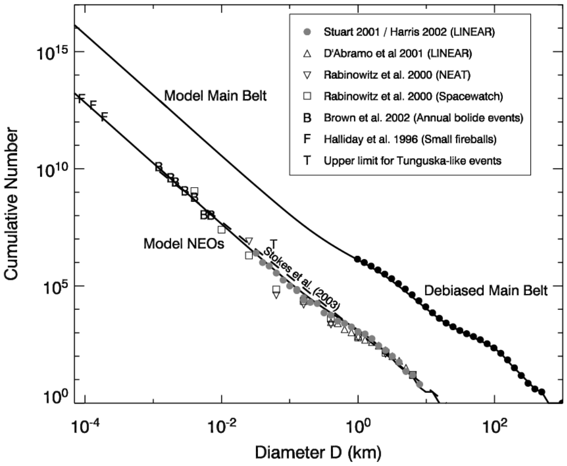

Fig. 2. The present-day main belt and NEA populations based on our model runs (solid lines). The shape of the NEA population is a reflection of the main belt, where Yarkovsky thermal drag causes D < 40 km asteroids to drift into resonances that in turn deliver them to the NEA population.

Using a debiased model of the orbit, size and spectral type distribution of the NEO and Mars-crossing asteroid populations [11, 17], we estimated the impact flux on each terrestrial planet. Note that our NEO orbit and size distribution was calibrated using NEO observations of the Spacewatch and LINEAR surveys. Our model predicts the collision of an NEO with absolute magnitude $H < 18$ with the Earth every 0.51 My, with a mean weighted impact velocity of 20.2 km/s. For comparison, the corresponding impact intervals and velocities are: 3.24 My and 42.2 km/s for Mercury, 0.51 My and 24.8 km/s for Venus and 1.1 My and 9.94 km/s for Mars. We can use these values to compute the frequency of collisions as a function of impact energy on the terrestrial planets. When convolved with standard crater formation scaling laws [18], our model predicts the formation of $\sim 3 \times 10^{-14}$ craters of 4 km in diameter per square kilometer per year on the Moon. This figure compares well with the estimate obtained from crater counting on lunar terrains with known ages.

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