THE EARLIEST LUNAR BOMBARDMENT PRODUCED BY MOON-FORMING IMPACT EJECTA.

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Introduction. The Moon likely formed in a collision between a large protoplanet and the proto-Earth [e.g., 1,2]. This giant impact (GI) occurred during the late stages of Earth's accretion; the abundance of highly siderophile elements in Earth's mantle indicate the Earth only accreted ~0.5% of its mass from broadly chondritic projectiles after this time [e.g., 3]. This makes the GI one of the youngest largest collisions to take place in the terrestrial planet region.

Recently, we used this inference to argue that GI ejecta dominated the population of km-sized bodies in the terrestrial planet region during the late stages of planet formation [4]. As evidence, consider that GI simulations, capable of reproducing Earth-Moon system constraints, often eject several percent of an Earth mass out of cis-lunar space [1-2]. If a considerable fraction of this mass were solid debris, as described by many GI simulations, and the GI ejecta size frequency distribution (SFD) had a steep slope, which we infer from modeling work and data [4], km-sized bodies could plausibly have struck main belt asteroids at velocities $V > 10$ km/s. This is enough to heat and degas target rock; models show such impacts produce ~1,000 times more highly heated material by volume than typical main belt collisions at ~5 km/s [5]. By tracking the temporal evolution of GI ejecta, we predicted a "signature" of the GI was left behind in the ^{40}Ar-^{39}Ar shock degassing ages of asteroid meteorites, and that they show the Moon formed ~4.48 Ga [4].

If GI ejecta blasted the asteroid belt, a large fraction should have also returned to hit the Moon. Here we examined whether the most ancient lunar craters and basins could plausibly come from these projectiles.

Dynamical Model of GI Ejecta. To explore the evolution of GI ejecta, we tracked 30,000 test bodies for 600 My using the numerical integrator SWIFT-RMVS3. The planets Venus-Neptune were included in the integrations with starting orbits described in [6]. For their initial orbits, the bodies were assigned a random isotropic trajectory away from Earth's center, were placed along Earth's Hill sphere, and were given an initial ejection velocity "at infinity" of 1, 3, 5, 7, or 9 km/s, respectively. The results were combined by weighing the outcomes using an initial velocity distribution corresponding to GI hydrocode simulations; 14%, 27%, 26%, 18%, and 15% of the objects were ejected at 1, 3, 5, 7, 9 km/s [7].

Using [8], we estimated that ~1% of our GI test bodies should have struck the Moon ~0.01-400 My after the GI. The timing and impact velocities V of the test bodies are shown in **Fig. 1**. We find that 30% and 65% hit within 1 and 10 My of the GI, respectively. Their median V was < 10 km/s. The last 35% hit between 10-400 My. Their median V was >10 km/s. Velocities increase as the test bodies are perturbed by the terrestrial planets.

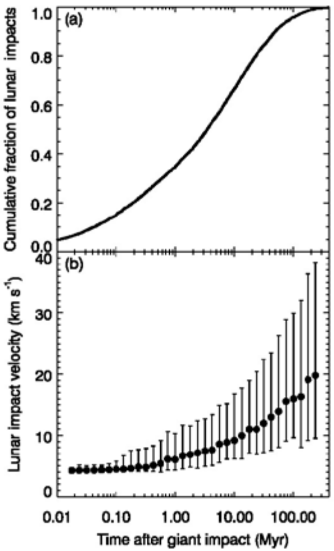

Fig. 1. GI ejecta hits the Moon

Collisional Evolution of GI Ejecta. A key uncertainty here is the nature of the GI ejecta SFD. We infer its properties in part from the ancient lunar impact record. The Moon has ~25 Pre-Nectarian (pN) lunar basins made by the impact of $D > 20$ km diameter projectiles [9]. Assuming 1% lunar accretion, the GI ejecta SFD only had a few thousand $D > 20$ km bodies. Mass balance therefore requires the majority of GI ejecta to be in a steep SFD dominated by $D < 20$ km bodies. Tests suggest that ~10^{10} km-sized projectiles were thrown out of cis-lunar space (**Fig. 2**) [4].

Support for such steep SFDs can be found in nature (e.g., Rheasilvia basin on (4) Vesta produced frag-

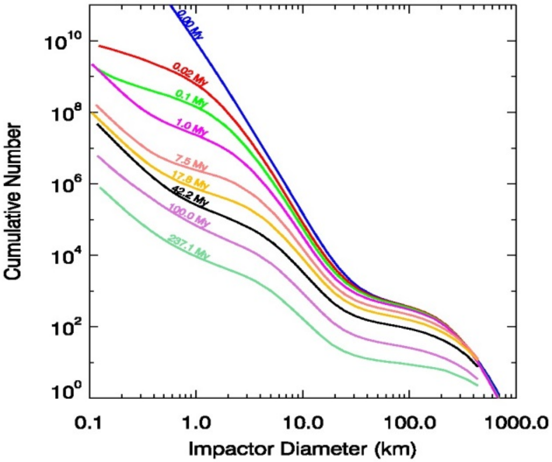

Fig. 2. Collisional evolution of GI ejecta over time.

ments with a steep cumulative power law SFD; exponents of -3.7 and -8 for diameter *D* > 3 km and > 5 km bodies, respectively) [10].

A consequence of a steep GI SFD is that the fragments should undergo vigorous collisional evolution with themselves (**Fig. 2**). Collision evolution codes indicate *D* < 1 km bodies undergo rapid demolition, enough to reduce the population by several orders of magnitude in mass within 0.1-1 My of the GI [11]. The surviving fragments develop a bump near *D* ~ 2 km that eventually evolves to 5-6 km as the SFD settles into a collisional steady state. At late times, most mass loss is produced by dynamical processes.

Comparing Model Results to Data. Combining results from Figs. 1 and 2, we can predict the SFD of GI projectiles that created pN craters and basins (**Fig. 3**). The blue and red curves show cumulative impacts 7.5 and 15 My after the GI, respectively (Fig. 3a). By converting these populations into craters, we find we can reproduce the oldest crater SFDs found on pN (green) and SPA (grey) terrains (Fig. 3b) [12].

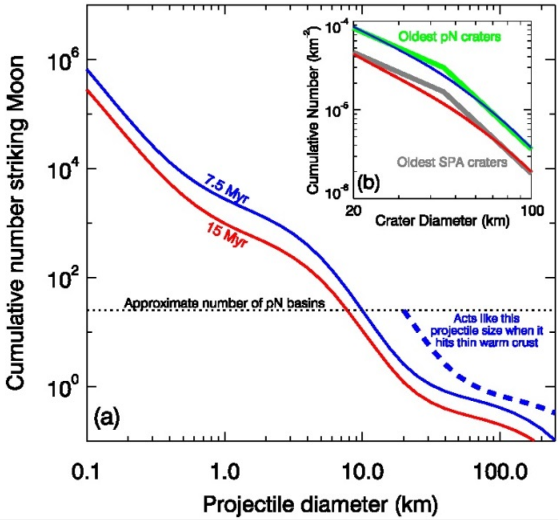

Fig. 3. (a) GI projectiles hitting Moon over 7.5 and 15 My; (b) pN craters compared to model results.

Here the bump in Fig. 3a near 3-4 km diameter projectiles corresponds to a bump observed in Fig. 3b for 40-50 km craters [12]. We predict these terrains formed 7.5 and 15 My after the GI, respectively. To account for pN basins, we assumed the early pN crust was thin and had high temperatures, low viscosities, and rheological properties broadly comparable to those that existed on the lunar nearside when Imbrium basin formed [13]. This may allow *D* > 10 km projectiles to act like larger projectiles (blue dashed line) and match the observed number of pN basins (black dashed line). This would also explain the absence of 120 km < *D* < 300 km craters on ancient Pre-Nectarian terrains [12].

Implications. There are several interesting implications that come from this scenario:

1. Considerable GI ejecta hit the Moon prior to the oldest pN terrains when the crust was thin, hot, and mushy. The consequences of such impact events are unknown, but we suspect they would leave behind features similar to *palimpsests*, the flat basins found on Callisto. Such outcomes could explain why several prominent pN basins (e.g., Tranquillitatis, Fecunditatis, Australe, perhaps Procellarum) lack the topographic and gravity signatures of younger basins [e.g., 14].

2. Numerous impacts breaching the early crust might allow the upper mantle to cool rapidly. This might explain why the ancient SPA basin managed to create a large topographic signature [e.g., 9].

3. Projectiles derived from the crust/mantle of the GI bodies may be lacking in FeNi. Impact melt pools created by these impactors will be missing the key material that can record a magnetic signature from the putative lunar dynamo [15]. This may explain why few pN basins have magnetic anomalies [16].

4. The SPA impact required 4×10^{26} J [17]. Assuming 100% accretion, an SPA projectile ~220 km in diameter striking at ~7 km/s could provide the Moon's HSE abundances [3]. Interestingly, this velocity is a good match to Fig. 1 and not so much to leftover planetesimals [18]. *Did SPA come from GI ejecta?*

5. If GI ejecta dominate early lunar bombardment, few major impacts occur on the terrestrial planets between ~4.45 and 4.1-4.2 Ga, the time of the Late Heavy Bombardment (LHB) [6]. The renewal of major impacts after a ~0.2-0.3 Gy "lull" might help to explain (i) why Mercury was resurfaced at the start of the LHB [19], (ii) why Earth's zircon record peaks at 4.1-4.2 Ga [20], and (iii) why few obvious Martian basins have been found to be older than Hellas [21].

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