# THE LATE HEAVY BOMBARDMENT OF THE MOON: A PROSPECTUS.

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**Motivating Problem.** The Lunar Late Heavy Bombardment (LHB) defines a time between $\sim 3.8$ to possibly 4.1 Gy ago when the basins on the Moon with reasonably well-constrained ages were formed (e.g., Nectaris, Serenitatis, Imbrium, Orientale) [e.g., 1,2]. This topic has been fraught with controversy ever since it was introduced as a means to explain the absence of lunar rocks with isotopic recrystallization ages $> 4.0$ Gy old [3]. Nearly all lunar impact melt breccia samples have been found to have ages between 3.8 and 4.0 Gy old (e.g., [4]). Some argue this curious result is best explained by a *terminal cataclysm* produced by a spike in the inner Solar System impactor flux between $\sim 3.8$-4.0 Ga [e.g., 5]. Others argue that the LHB was actually the tail end of a monotonically decreasing impactor population originally produced by planet formation processes in the inner Solar System (i.e., the *declining bombardment*) [e.g., 1].

Understanding the nature of the LHB will allow us to determine how and when the planets of the Solar System reached their final configuration. Indeed, it will supply crucial clues to the temporal evolution of the planetary system as a whole. Moreover, we will be able to glean important insights into how this barrage of impactors in the inner Solar System affected the evolution of life on Earth (and possibly Mars as well). In this prospectus, we will briefly describe the current state of the art of LHB dynamical models and what new observations on the Moon could help us further constrain these models and, most likely, determine which (if any) actually represent what happened.

**Declining Bombardment Model.** Perhaps the simplest explanation for the late formation of young basins is that they were formed by planetesimals that originated in the terrestrial planet region. Here it is assumed that evolving planetary embryos in the terrestrial planet region scatter numerous planetesimals into long lived high inclination orbits. Accordingly, this population of planet formation leftovers produces a slow-decaying bombardment on the Moon (and other terrestrial planets) that lasts from the Moon's formation all the way to $\sim 3.8$ Ga.

This scenario was recently investigated by [6], who numerical modeled the evolution of the post-planet formation population (PPP) for a range of starting masses. Their goal was to determine whether the declining bombardment could realistically reproduce the Nectaris, Serenitatis, Imbrium, and Orientale basins at their inferred ages between 3.8-4.1 Ga [2]. To their surprise, they found that collisional and dynamical evolution quickly depletes the PPP, leaving behind a paucity of large projectiles capable of producing the Moon's youngest basins. The estimated the odds of forming the aforementioned basins at their reported ages was $< 0.1$%, regardless of the PPP's starting mass. They also found the declining bombardment produced numerous South Pole-Aitken-like basins during the pre-Nectarian period, results that are inconsistent with our understanding of lunar topography. Accordingly, the declining bombardment scenario was not considered viable from a dynamical modeling perspective nor was it found to be consistent with existing lunar constraints.

**Terminal Cataclysm Model.** If the LHB was a spike, then it implies that the dynamical state of the planetary system changed some 600 Myr after the planets formed. Recent dynamical modeling work [7, 8, 9] presents a plausible scenario for the early evolution of the giant planets that not only includes such a violent reshuffling of the planets, which reproduces the terminal cataclysm, but also explain many other longstanding problems in Solar System dynamics. The papers [7, 8, 9] are commonly referred to as the "Nice" model, named after the Observatoire de la Côte d'Azur in Nice, France where it was developed.

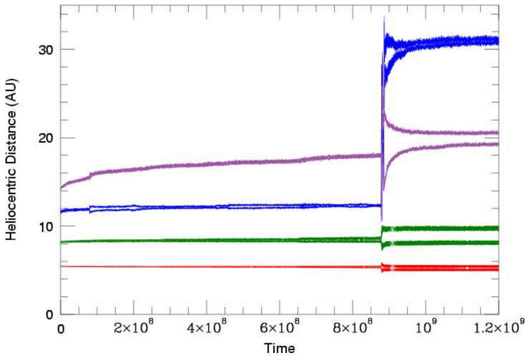

**Figure 1:** Planetary evolution of Jupiter (red), Saturn (green), Uranus (purple), and Neptune (blue) as predicted by the Nice model. Top/bottom curves for each planet are aphelion $Q$ and perihelion $q$ distances. Jupiter and Saturn cross the 1:2 MM resonance at 880 My. The interaction throws Uranus/Neptune into comet disk, where they migrate to their current orbits.

The Nice model takes advantage of several newly quantified concepts in planet formation studies. Here the Jovian planets are assumed to have formed on initially nearly circular, coplanar orbits with a more compact configuration than they have today (all were located between 5-15AU). Slow planetary migration was induced in the Jovian planets by gravitational interactions with planetesimals leaking out of a $\sim 35 M_\oplus$ planetesimal disk residing between $\sim 16$ to $\sim 30$ AU (i.e., known as the primordial trans-planetary belt). These interactions steadily stretched the system of planets over hundreds of My (Fig.1). Eventually, after a delay of

$\sim$ 600 My ($\sim$ 3.9 Ga) that was set by the initial configuration of the gas giants, Jupiter and Saturn crossed their mutual 1:2 mean motion resonance, which caused their eccentricities and inclinations values to jump from near zero to their current values. In turn this caused Uranus and Neptune to become unstable and be scattered outward, such that they penetrated the disk and migrated through it. The orbits of Uranus and Neptune were then circularized by dynamical friction produced by bodies in the disk, allowing them to reach their current orbits.

The migration of Uranus and Neptune through the primordial trans-planetary belt quickly scattered the population and caused numerous comets to slam into the Moon and terrestrial planets. Moreover, the migration of Jupiter and Saturn caused secular resonances to sweep across the main asteroid belt; numerical simulations indicate that up to 90% of the main belt could have been ejected into the terrestrial planet region by these actions. Thus, LHB impactors were may have been a combination of cometary bodies scattered by Uranus/Neptune and asteroids pushed out of the main asteroid belt (Fig. 2).

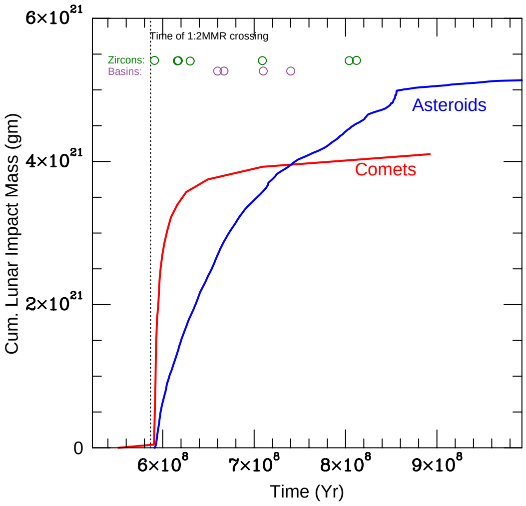

**Figure 2:** The lunar LHB impactor flux $\sim$ 3.9 Ga according to the Nice terminal cataclysm model. The duration of the impact spike is 150-200 My, with comets dominating first 30 My and asteroids dominating for the next 150 My. The timing and mass flux of the impactors matches constraints from lunar basins.

The Nice model is a compelling scenario in part because it can reproduce lunar LHB constraints but also because it explains the orbits of the Jovian planets and small body reservoirs in the outer solar system (e.g., Trojans of Jupiter and Neptune, the Kuiper belt and scattered disk, the irregular satellites of the giant planets, and the curious presence of dormant comets in the outermost regions of the asteroid belt). These accomplishments are unique among models of outer solar system formation. Moreover, this model makes specific predictions the early impact history of the terrestrial planets and the composition/timing of the impacting bodies. For example, the impact rate on the Moon and presumably the other terrestrial planets was probably minimal for hundreds of My prior to the terminal cataclysm 3.9 Ga. This may have been enough time for primitive life to gain a foothold on the Hadean-era Earth. In addition, the LHB may have also delivered sufficient water to Mars 3.9 Ga to explain its morphology [11].

**Returning to the Moon.** While current numerical work favors the terminal cataclysm, existing lunar constraints do not yet provide a "smoking gun" for this or any other LHB model. For example, the basins formed in the pre-Nectarian period, which comprises the earliest observable phase of lunar history, have little to no age constraints. Most pre-Nectarian basins reside on the far side of the Moon where we lack samples other than those from lunar meteorites that have yet to placed into context. Moreover, the age of the Nectaris basin is ambiguous, with a range that could be relatively young (3.85 Ga) or surprisingly old (4.12 Ga or older). It is exactly this information that could be used to help us better determine the nature of the LHB as well as the impact flux on the Moon (and Earth) prior to the LHB.

We believe that determining the timing of lunar basin formation as well as the composition of the projectiles making each basin should be considered a critical priority in the next phase of the Moon's exploration. Moreover, some of the arguments used to justify a return to the Moon could easily be reframed to focus on the Moon's singular importance to our understanding of the very late stages of planet formation. Recall that if the Nice terminal cataclysm model is correct, the Moon provides the best and most accessible witness plate for what may well be described as the complete reorganization of the Solar System $\sim$ 3.9 Ga. We find a mission to the Moon to probe this idea to be one that could captivate the planetary science community and inspire budding scientists who will enter the field as the new lunar landings take place over the next decade.

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