Origin of the Cataclysmic Late Heavy Bombardment of the Terrestrial Planets

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The petrology record on the Moon suggests a cataclysmic spike in the cratering rate ~ 700 million year after the planets formed [1], known as the Late Heavy Bombardment (LHB). Planetary formation theories cannot naturally account for an intense period of planetesimal bombardment so late in Solar System history [2]. Several models have been proposed to explain a late impact spike [3-6], however, none of them has been built in a self-consistent framework of Solar System evolution. Here, we propose that the LHB was triggered by the rapid migration of the giant planets, which occurred after a long quiescent period. During this burst of migration, the planetesimal disk outside the orbits of the planets was

destabilized causing a sudden massive delivery of planetesimals to the inner Solar System. The asteroid belt was also strongly perturbed, so that, according to this model, the asteroids would have supplied a significant fraction of the LHB impactors, in accordance with recent geochemical evidence[7,8]. Our model not only naturally explains the LHB, but also reproduces the observational constraints of the outer Solar System[9].

Previous work [9] explains the current orbital architecture of the planetary system by invoking an initially compact configuration in which Saturn's orbital period was less than twice that of Jupiter. After the dissipation of the gaseous circumsolar nebula, as a result of their interaction with a massive disk of planetesimals, Jupiter's and Saturn's orbits diverged and thus the ratio of their orbital periods, P_S/P_J, increased. When the two planets crossed their mutual 1:2 mean motion resonance (1:2 MMR, i.e. $P_S/P_J = 2$) their orbits became eccentric. This abrupt transition temporarily destabilized the giant planets, leading to a short phase of close encounters among Saturn, Uranus and Neptune. As a result of these encounters, and of the interactions of the ice giants with the disk, Uranus and Neptune reached their current heliocentric distances and Jupiter and Saturn evolved to their current orbital eccentricities [9]. The main idea of this *letter* is that the same planetary evolution could explain the LHB, provided that Jupiter and Saturn crossed the 1:2 MMR roughly 700 Myr after they formed. Thus, our goal is to determine if there is a generic mechanism that could delay the migration process.

In previous works [9-12], planet migration started immediately because planetesimals were placed close enough to the planets to be violently unstable. While this type of initial condition was reasonable for the goals of those works, it is unlikely. Planetesimal driven migration is probably not important for planet dynamics as long as the gaseous massive solar nebula exists. The initial conditions for the migration simulations should represent the system that existed at the time the nebula dissipated. Thus, the planetesimal disk should contain only those particles that had dynamical lifetimes longer than the lifetime of the solar nebula. In planetary systems like those we adopt from [9], we find that they had to be beyond $\sim$15.3 AU (Figure 1), leading to the initial conditions illustrated in Figure 2a.

In this configuration, the initial speed of migration would be dependent on the rate at which disk particles evolve onto planet-crossing orbits. The time at which Jupiter and Saturn cross their 1:2 MMR depends on: 1) their initial distance from the location of the resonance, 2) the surface density of the disk near its inner edge, and 3) the relative location of the inner edge of the disk and the outer ice giant. Based on the above arguments, we initially performed a series of 8 simulations where the location of the inner edge of the disk was set as the unique free parameter (Figure 1). As expected we found a strong correlation between the location of the inner edge and the time of the 1:2 MMR crossing. For disks with inner edges near 15.3 AU (see above), we find crossing times between 192 Myr and 875 Myr.

We also performed 8 simulations where we varied the initial location of the ice giants by ~ 1 AU, Saturn's location by ~ 0.1 AU, the total mass of the disk by $5\,M_E$, and its initial dynamical state by pushing the particles' eccentricities up to 0.1 and inclinations up to 3.5°. We found that we can delay the resonant crossing to 1.1 Gyr, although longer times are clearly possible for more extreme initial conditions. Therefore, we can conclude that the global instability caused by the 1:2MMR crossing of Jupiter and Saturn could be responsible for the LHB, since the estimated date of the LHB falls in the range of the times that we found.

Figures 2 and 3 show the evolution of one of our runs from the first series of 8. Initially, the giant planets migrated slowly due to leakage of particles from the disk (Figure 3a). This phase lasted 875 Myr, at which point Jupiter and Saturn crossed the 1:2 MMR. After the resonance crossing event, the orbits of the ice giants became unstable and they were scattered into the disk by Saturn. They disrupted the disk and scattered objects all over the Solar System, including the inner regions. The solid curve in Figure 3b shows the amount of material that struck the Moon as a function of time. A total $9 \times 10^{21} g$ impacted the Moon after resonance crossing — roughly 50% of this material arrived in the first 3.7 Myr and 90% arrived before 29 Myr. The total mass is consistent with the observed estimates [4] of 6×10^{21} g, which were determined from the number and size distribution of lunar basins that formed around the time of the LHB epoch [1]. Such an influx spike happened in all our runs. The amount of cometary material delivered to the Earth is $\sim 1.8 \times 10^{23}$ g, namely about 6% of the current ocean mass. This is consistent with upper bounds on the cometary contribution to the Earth water budget, based from D/H ratio measurements[21]. The average amount of material accreted by the Moon during this spike was $8.4 \times 10^{21} \pm 3 \times 10^{20}$ g.

The above mass delivery estimate corresponds only to the cometary contribution to the LHB, as the projectiles originated from the external massive, presumably icy disk. However, our scheme most likely also produced an influx of material from the asteroid belt. As Jupiter and Saturn moved from the 1:2 MMR towards their current positions, secular resonances (which occur when the orbit of an asteroid precesses at the same rate as a planet) swept across the entire belt [15]. These resonances can drive asteroids onto orbits with large enough eccentricities and inclinations that their orbits are no longer stable and they can evolve into the inner solar system and hit the Moon [4].

We investigated the role of asteroid impactors in our LHB model by the following numerical integrations. The orbits of an asteroid belt, composed of 1,000 massless particles with semi-major axes between 2.0 and 3.5 AU were integrated under the gravitational influence of the Sun, Venus, Earth, Mars, Jupiter and Saturn. Since formation models [16,17] predict that the asteroid belt was partially depleted and dynamically excited well before the LHB, we set the particles' eccentricities between 0 and 0.3 and inclinations between 0 and 30 degrees, but kept the perihelion distances, $q > 1.8\,\mathrm{AU}$ and aphelion distance, $Q < 4\,\mathrm{AU}$. Jupiter and Saturn were forced to migrate at rates that varied from run to run (adopted from [9]) by adding a suitably chosen drag-force term to their equations of motion.

We find that objects that reach Earth-crossing orbits follow one of two general paths. Some, known as Class 1, get trapped in the periapse secular resonance with Saturn (which effects eccentricities) and are driven directly onto Earth-crossing orbits. Other particles, known as Class 2, stay in the asteroid belt, but are dynamically excited by resonant sweeping onto unstable orbits. These objects slowly leak out of the asteroid belt and can evolve into the inner Solar System. The two classes produce impact spikes with different temporal behaviors. Roughly 50% of Class 1 arrive in the first 10 Myr, while 90% arrive within $\sim$30Myr. Conversely, the median arrival time for Class 2 is $\sim$50 Myr and 90% arrive within $\sim$150Myr. Class 2 particles dominated in our runs (Figure 3). However, a preliminary investigation into this issue shows that this result is likely sensitive to the exact evolution of the giant planets and the dynamical state of the asteroid belt. Thus, the best we can conclude is that the impact spike due to asteroids is between these two extremes.

We find that between 3×10^{21} and 8×10^{21} g of asteroids hit the Moon during our simulations (Figure 3). This amount is comparable to the amount of comets. So, our model predicts that the LHB impactors should have been a mixture of comets and asteroids. Unfortunately, we cannot say with any certainty the exact ratio of comets to asteroids in our model because, although the amount of cometary material is fairly well constrained (probably better than a factor of 2), the amount of asteroidal material is not well known (and could be outside of the range reported above), because we do not have good estimates of the mass distribution in the asteroid belt pre-LHB. It should also be noted that this ratio is probably a function of impactor size because comets and asteroids probably have different size distributions. This ratio probably also varied with time. Within the first $\sim$30 Myr, comets dominated according to these simulations, but the last impactors were asteroidal. This is consistent with recent cosmochemical findings suggesting that some of the Moon's basins were formed by asteroids [7,8].

Our results support a cataclysmic model for the lunar LHB. Although many aspects of the LHB are not well known [1], our simulations reproduce two of the main characteristics attributed to this episode: 1) the 700 Myr delay between the LHB and terrestrial planet formation and 2) the overall intensity of lunar impacts. Our model predicts a sharp increase in the impact rate at the beginning of the LHB. Unfortunately, the available lunar data is not yet capable of addressing this prediction.

Our model also has the advantage of supplying impactors that are a mixture of comets and asteroids. Our model predicts that the asteroid belt was depleted by a factor of ~ 10 during the LHB. This depletion does not contradict collisional evolution models[18,19]. On the contrary, the late secular resonance sweeping could explain why we do not see a large number of asteroid families that were produced during the LHB[19]. Our model predicts that the LHB lasted from between $\sim$ 10 My and $\sim$ 150 My. Correspondingly, the drop off in impact rates could be quite fast (with 50% of the impacts occurring in the first 3.7 Myr and 90% in 29 Myr) or moderately slow (with 50% of the impacts occurring in the first 50 Myr and 90% in 150 Myr). We are unable to pinpoint more exact values because the duration and the drop-off of the LHB depends on the relative contributions of Class 1 asteroids, Class 2 asteroids, and comets, which in turn, are very sensitive to the pre-LHB orbital structure of the asteroid belt.

Most importantly, our scheme for the LHB is the result of a generic migration-delaying mechanism, followed by an instability, which is itself induced by a deterministic mechanism of orbital excitation of the planets [9]. This revised planetary migration scheme naturally accounts for the currently observed planetary orbits [9], the LHB, the present orbital distribution of the main-belt asteroids and the origin of Jupiter Trojans[20].

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Figure Captions:

Figure 1: Disk location and LHB timing. (a) The histogram reports the average dynamical lifetime of massless test particles placed in a planetary system (shown as triangles) with Jupiter, Saturn and the ice giants on nearly-circular, co-planar orbits at 5.45, 8.18, 11.5, 14.2 AU, respectively. Initially, we placed 10 particles with $e = i = 0$ and random mean anomaly at each semi-major axis. Stable Trojans of the planets have been removed from this computation. Each vertical bar in the plot represents the average lifetime for those 10 particles. We define 'dynamical lifetime' as the time required for a particle to encounter a planet within a Hill radius. A comparison between the histogram and the putative lifetime of the gaseous nebula [13], argues that, when the latter dissipated, the inner edge of the planetesimal disk had to be about 1–1.5 AU beyond the outermost ice giant. (b) Time at which Jupiter and Saturn crossed the 1:2 MMR, as a function of the location of the planetesimal disk's inner edge, as determined from our first set of migration simulations. In all cases the disk had a surface density equivalent to 1.9 Earth-masses ($\mathrm{M_E}$) per 1AU annulus. The outer edge of the disk was varied so that the total mass of the disk was $35\,M_E$. The disk was initially very dynamically cold, with eccentricities, e, equal to 0 and inclinations, i, less

than 0.5°. A comparison between (a) and (b) shows that a disk that naturally should exist when the nebula dissipated would produce a 1:2MMR crossing at a time comparable to that of the LHB event.

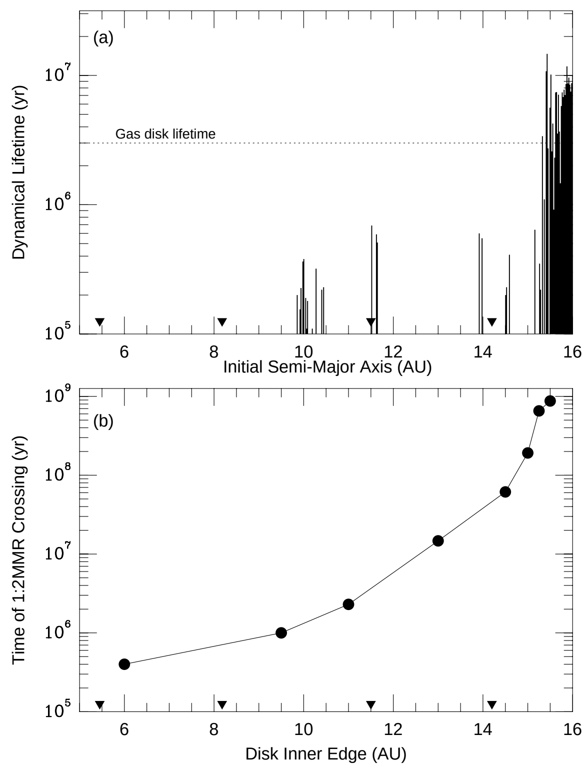
Figure 2: The planetary orbits and the positions of the disk particles, projected on the initial mean orbital plane. The four panels correspond to four different snapshots taken from our reference simulation. In this run the 4 giant planets were initially on nearly-circular, co-planar orbits with semi-major axes of 5.45, 8.18, 11.5, 14.2 AU. The dynamically cold planetesimal disk was 35 M_E with an inner edge at 15.5 AU and an outer edge at 34 AU. Each panel represents the state of the planetary system at four different epochs: (a) the beginning of planetary migration (100 Myr), (b) just before the beginning of LHB (879 Myr), (c) just after the LHB has started (882 Myr) and (d) 200 Myr later, when only 3% of the initial mass of the disk is left and the planets have achieved their final orbits.

Figure 3: Planetary migration and the associated mass flux towards the inner Solar System from a representative simulation. (a) The evolution of the 4 giant planets. Each planet is represented by a pair of curves – the top and bottom curves are the aphelion and perihelion distances, respectively. Jupiter and Saturn cross the 1:2 MMR at 880 Myr. The subsequent interaction be-

tween the planets and the disk led to the current planetary configuration as shown in [9]. (b) The cumulative mass of comets (solid curve) and asteroids (dashed curve) accreted by the Moon. We have offset the comet curve so that the value is zero at the time of 1:2MMR crossing. Thus, $\sim 5 \times 10^{21} g$ of comets was accreted before resonant crossing and $9 \times 10^{21} g$ of cometary material would have struck the Moon during the LHB. Although the terrestrial planets were not included in our cometary simulations, we estimated the amount of material accreted by the Moon directly from the mass of the planetesimal disk by combining the particles' dynamical evolution with the analytic expressions in [14]. The impact velocity of these objects ranged from 10 km/sec to 36 km/sec with an average of 21 km/sec. Estimating the asteroidal flux first requires a determination of the mass of the asteroid belt before resonant crossing. This value was determined by first combining the percentage of asteroids remaining in the belt at the end of a simulation ($\sim$10%, very sensitive to planet migration rate and initial asteroid distribution) with estimates of the current mass of the belt to determine the initial asteroid belt mass ($\sim 5 \times 10^{-3}\,\mathrm{M_E}$). The flux was then again determined by combining the particles' dynamical evolution with the analytic expressions in [14]. The dotted curve shows a simulation where Class 2 particles dominate.

The average asteroidal impact velocity is 25 km/sec.

Figure 1:



(a)
Dynamical Lifetime (yr)
Gas disk lifetime
10^7
10^6
10^5
6
8
10
12
14
16
Initial Semi-Major Axis (AU)
(b)
Time of 1:2MMR Crossing (yr)
10^9
10^8
10^7
10^6
10^5
6
8
10
12
14
16
Disk Inner Edge (AU)

Figure 2:

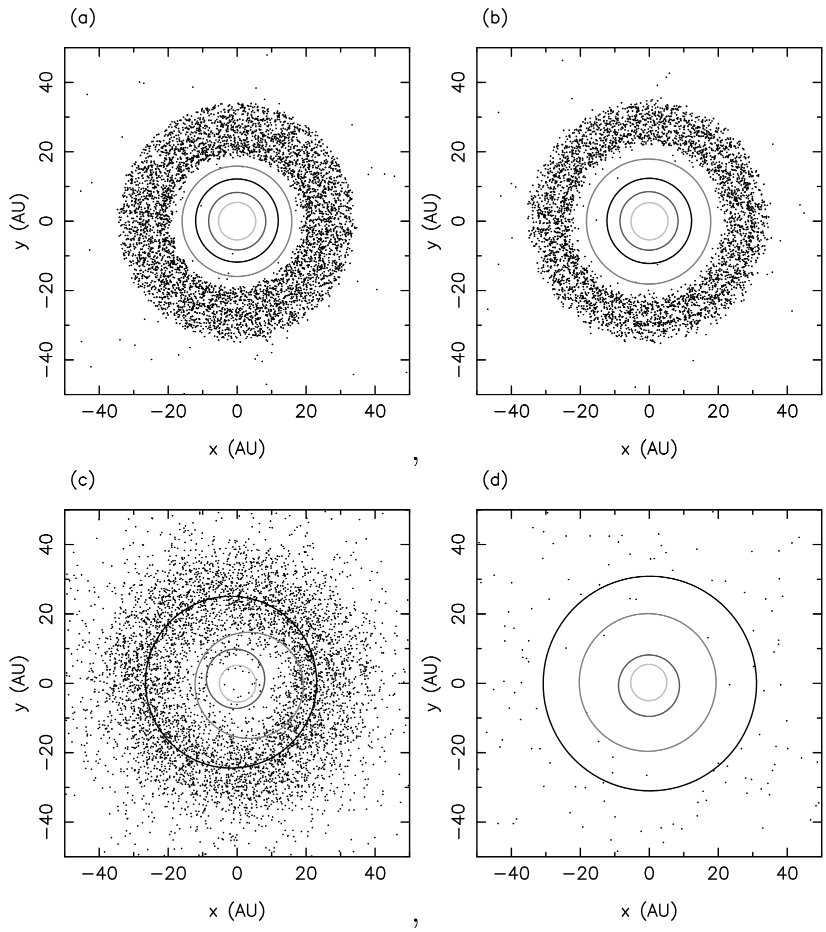
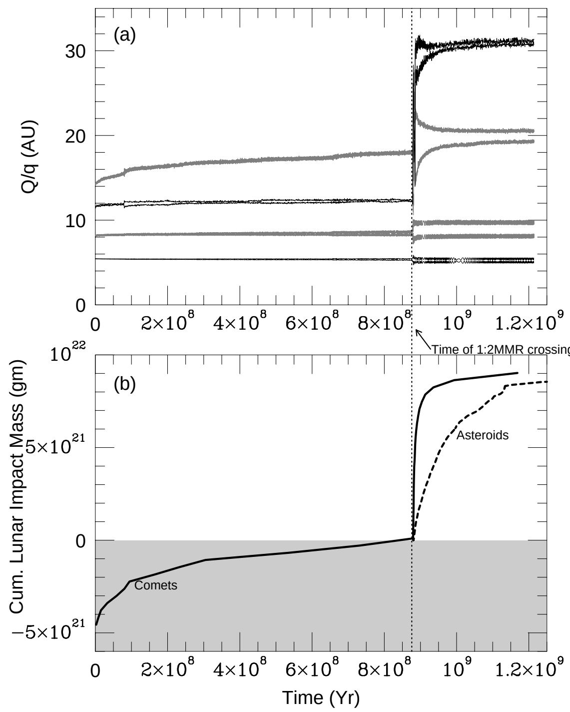


Figure 3:



(a)
Q/q (AU)
30
20
10
0
0
2×10^8
4×10^8
6×10^8
8×10^8
10^9
1.2×10^9
Time of 1:2MMR crossing
(b)
10^22
Cum. Lunar Impact Mass (gm)
5×10^21
0
−5×10^21
Asteroids
Comets
Time (Yr)