Dynamics of Celestial Bodies, 67 - 76 *Invited paper*

A BRIEF REVIEW OF THE LATE HEAVY BOMBARDMENT

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Abstract. I briefly review the evidence for a cataclysmic Late Heavy Bombardment of the Moon and of the Terrestrial planets. Then, I discuss a model of the evolution of the outer solar system that has been developed to explain the origin of such cataclysm (the often-called "Nice model") as well as its competing model, based on the existence of a rogue 5th terrestrial planet.

1. INTRODUCTION

One might think that, when the planet ended their accretion process, approximately 100 My after the formation of the first solids (Touboul et al., 2007) the Solar System looked essentially like the one in which we currently live. However, this was probably not the case. One event, called the Late Heavy Bombardment (LHB), suggests that the Solar System had to have a structure that was different from the current one and that something happened about 600 My after planet formation.

Below, I first review the observational constraints on the LHB, and then I describe the models proposed to explain this event.

2. EVIDENCE FOR A LATE CATACLYSMIC BOMBARDMENT

The crust of the Moon crystallized around 4.44 Gy ago, and the morphology of its highlands records a dense concentration of impact craters, excavated prior to the emplacement -around 3.8 Gy ago- of the first volcanic flows in the mare plains (Wilhems, 1987). Thus, a period of intense bombardment -the LHB- occurred in the first 600-700 My of the Moon's history. However, the magnitude and the chronology of the collisions between 4.5 and 4 Gy remains a topic of controversy.

Two explanations have been proposed. According to Hartmann (1975), the frequency of impacts declined slowly and progressively after the end of the accretion period, up to 3.9 Gy ago. In this view, the LHB is not an exceptional event. Rather, it is a 600 My tail of the collisional process that built the terrestrial planets.

Another view advocates a rapid decline in the frequency of impacts after the formation of the Moon, down to a value comparable to the current one. This was followed by a cataclysmic period between ∼4.0 and ∼3.8 Gy ago, marked by an extraordinarily high rate of collisions (Tera et al., 1974; Ryder, 1990; Cohen, 2000; Ryder, 2000; Ryder, 2002).

Today, the majority of experts favor the cataclysmic scenario of the LHB. This theory is supported by a series of arguments:

i) 600 million years of continual impacts should have left an obvious trace on the Moon. So far, no such trace has been found. The isotopic dating of the samples returned by the various Apollo and Luna missions revealed no impact melt-rock older than 3.92 Gy (Ryder, 1990, 2000). The lunar meteorites confirm this age limit. The meteorites provide a particularly strong argument because they likely originated from random locations on the Moon (Cohen, 2000), unlike the lunar samples collected directly at specific sites on its surface. A complete resetting of all ages all over the Moon is possible (Grinspoon, 1989) but highly unlikely, considering the difficulties of completely resetting isotopic ages at the scale of a full planet (Deutsch and Scharer, 1994).

ii) The old upper crustal lithologies of the Moon do not show the expected enrichment in siderophile elements (in particular the Platinum Group Elements) implied by an extended period of intense collisions (Ryder, 2000).

iii) If the elevated mass accretion documented in the period around 3.9 Gy is considered to be the tail end of an extended period of collisions, the whole Moon should have accreted at about 4.1 Gy ago instead of 4.5 Gy (Ryder, 2002; Koeberl, 2004).

iv) At least 2 (Imbrium and Orientale) and possible 4 (adding Nectaris and Serenitatis) of the largest impact structures on the Moon, the so-called basins, with diameters between 300 and 1,200 km, have been dated to have formed between 4.0 and 3.8 Gy ago. If the bombardment had declined monotonically since 4.5 Gy ago, it appears statistically improbable that such large impacts occurred at the end of the period (Bottke et al., 2007).

v) On Earth, the oxygen isotopic signature of the oldest known zircons (age: 4.4 Gy) indicates formation temperatures compatible with the existence of liquid water (Valley et al., 2002). This argument seems contradictory with an extended period of intense collisions, which would have raised the Earth's temperature to exceed the water evaporation threshold.

vi) These same zircons retain secondary overgrowths developed after primary core crystallization during their 4.4 Gy-long crustal residence times. The rim overgrowths can record discrete thermal events subsequent to zircon formation and provide a unique window in crustal processes before the beginning of the terrestrial rock record. In (Trail et al., 2006), all these rim overgrowths have been dated to be ∼3.9 Gy old. No (preserved) older rim overgrowths, associated to more primordial events, have been found. This suggests that the thermal events were associated to impacts, and that these impacts were concentrated in time about 3.9 Gy ago.

Therefore, it can be concluded that there is strong evidence for a cataclysmic Late Heavy Bombardment event around 3.9 Gy ago. This cataclysm did not just affect the Moon, but it has now been clearly established throughout the inner Solar System (Kring and Cohen, 2002). The study of the surface morphology of Iapetus (a satellite of Saturn) suggests that the LHB affected also the objects of the outer solar system (Johnson et al., 2008). The exact duration of the cataclysm is difficult to estimate, however. Based on the cratering record of the Moon, it lasted between 50 and 200 My, depending on the mass flux estimate used in the calculation.

3. THE NICE MODEL OF THE ORIGIN OF THE LHB

A model that aims to explain the origin of the LHB, in the framework of a comprehensive scenario of the late evolution of the Solar System, has been developed by a group gathered at the Nice Observatory in France, and for this reason is often called the Nice model (Tsiganis et al., 2005; Morbidelli et al., 2005; Gomes et al., 2005). This model is based on the concept of planetesimal-driven migration of the giant planets, which we briefly review below.

It was shown for the first time in Fernandez and Ip (1984) that, after the disappearance of the gas, while scattering away the primordial planetesimals from their neighboring regions, the giant planets had to migrate in semi-major axis as a consequence of angular momentum conservation. Given the configuration of the giant planets in our Solar System, this migration should have had a general trend. Uranus and Neptune have difficulty ejecting planetesimals onto hyperbolic orbits. Apart from the few percent of planetesimals that they can permanently store in the Oort cloud (Dones et al. 2004), or emplace onto long-lived orbits in the trans-Neptunian region (Duncan and Levison, 1997), the large majority of the planetesimals that are under the influence of Uranus and Neptune are eventually scattered inwards, towards Saturn and Jupiter. Thus, the ice giants, by reaction, have to move outwards. Jupiter, on the other hand, eventually ejects from the Solar System almost all of the planetesimals that it encounters: thus it has to move inwards. The fate of Saturn is more difficult to predict, a priori. However, modern numerical simulations show that this planet also moves outwards, although only by a few tenths of an AU for reasonable disk's masses (Hahn and Malhotra, 1999; Gomes et al., 2004).

Starting from two key considerations:

i) giant planet migration through the planetesimal disk induces a bombardment of the terrestrial planets of sufficient magnitude to explain the LHB (Levison et al., 2001),

ii)at the end of the migration phase, the Solar System is essentially identical to the current one (namely there are no more reservoirs of planetesimals to destabilize),

the Nice model group realized that solving the problem of the LHB origin required to find a plausible mechanism that would trigger planet migration at a late time.

Pursuing this goal, Gomes et al (2005) remarked that, in all previous simulations, 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 to have been the case in reality. In fact, planetesimal driven migration is probably not important for planetary dynamics as long as a gaseous massive nebula exists (the nebula accounts for about 100 times more mass than the planetesimals and it pushes the planets inwards and towards each other by Type I and Type II migration). The initial conditions in simulations of the planetesimal driven migration should therefore 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 (a few million years), because the planetesimals initially on orbits with shorter dynamical lifetimes should have been eliminated earlier, during the nebula era (ejected or stored in the Inner Oort Cloud), without major consequences on the planetary orbits. If this constraint on the initial conditions is fulfilled, then the resulting migration is necessarily slow, because it depends on the rate at which disk particles evolve onto planet-crossing orbits, which is of order of millions of year by the very definition of the initial conditions.

If the planetary system, in the absence of planetesimals, is stable, this slow migration can continue for a long time, slightly accelerating or damping depending on the disk's surface density (Gomes et al., 2004). Conversely, if the planet system is -or becomes- unstable, then the planets tend to increase abruptly their orbital separations. The outermost planet penetrates into the disk and this starts a fast migration, similar to that obtained in previous simulations, where the planets were embedded in the disk from the very beginning. Thus the problem of triggering the LHB is reduced to the problem of understanding how the giant planets, during their slow migration, could pass from a stable configuration to an unstable one.

A solution to this problem has been proposed in Tsiganis et al. (2005). This work postulated that, at the time of the dissipation of the gas disk, the four giant planets were in a compact configuration, with quasi-circular, quasi-coplanar orbits (as predicted by planet formation models) and with orbital radii ranging from 5.5 to 13-17 AU. Saturn and Jupiter were close enough to have a ratio of orbital periods less than 2. This choice of the initial orbital radii for the giant planets was originally just a working hypothesis. We now know that Type I and Type II migration drive the planets into a fully resonant configuration, with Jupiter and Saturn's periods in 2:3 ratio (Morbidelli et al., 2007). The non-resonant initial conditions of Tsiganis et al. (2005) can be considered representative of a case in which strong turbulence in the disk prevented permanent resonant locking (Adams et al., 2008). Assuming that turbulence was not strong enough, Morbidelli et al. (2007) re-did the simulations of Tsiganis et al. starting from a fully resonant configuration and obtained evolutions analogue of those of Tsiganis et al.. Thus below we focus on the description of the results of Tsiganis et al., because they carried a more detailed statistical analysis.

In Tsiganis et al., during their planetesimal-driven divergent migrations Jupiter and eventually crossed their mutual 1:2 mean-motion resonance. Resonance crossing during divergent migration leads to a passage without capture through the resonance, correlated with a sudden excitation of the orbital eccentricities. The enhanced eccentricities of Jupiter and Saturn destabilized the planetary system as a whole. The planetary orbits became chaotic and started to approach each other. Thus, a short phase of encounters followed the resonance-crossing event. Consequently, both ice giants were scattered outwards, deep into the disk. As discussed above, this abruptly increased the migration rates of the planets. During this fast migration phase, the eccentricities and inclinations of the planets decreased as a result of the dynamical friction exerted by the planetesimals and the planetary system was finally stabilized.

With a planetesimal disk of about 35 Earth masses and extended up to 35 AU, the simulations in Tsiganis et al. reproduced the current architecture of the orbits of the giant planets remarkably well, in terms of semi-major axes, eccentricities and inclinations. In particular, this happened in the simulations where at least one of the ice giants encountered Saturn (see Fig. 1). Conversely, in the simulations where encounters with Saturn never occurred, Uranus typically ended its evolution on an orbit too close to the Sun and the final eccentricities and inclinations of all the planets were too small.

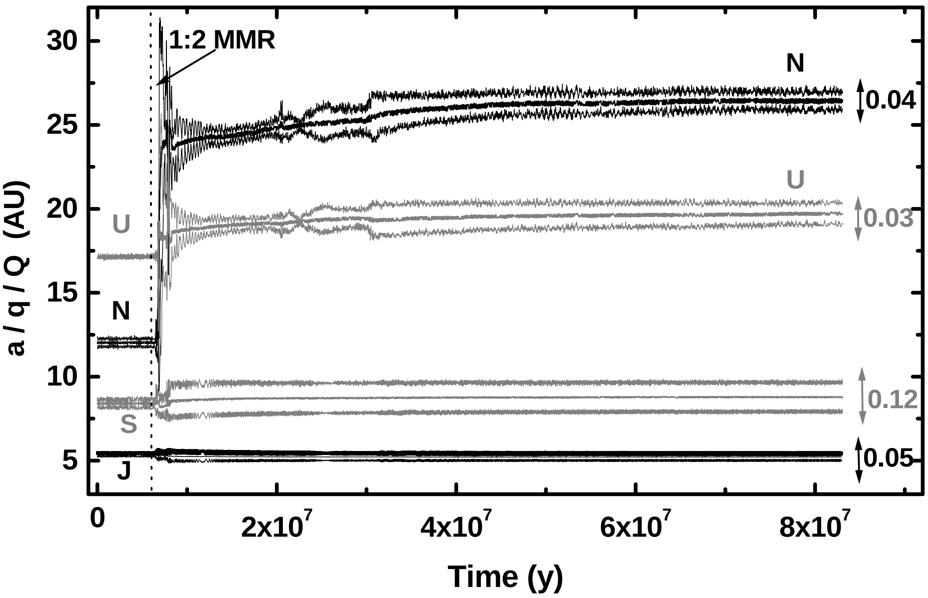

Figure 1: Comparison of the synthetic final planetary systems obtained in Tsiganis et al. (2005) with the real outer Solar System. Top: Proper eccentricity vs. semi-major axis. Bottom: Proper inclination vs. semi-major axis. Here, proper eccentricities and inclinations are defined as the maximum values acquired over a 2 My time-span and were computed from numerical integrations. The inclinations are measured relative to Jupiters orbital plane. The values for the real planets are presented as filled black dots. The black squares mark the mean of the proper values for the runs with no planetary encounters involving Saturn, while the grey squares mark the same quantities for the runs where at least one ice giant encountered the ringed planet (about 15 runs in each case). The error bars represent one standard deviation of the measurements.

With this result in hands, Gomes et al. (2005) could put all the elements together in a coherent scenario for the LHB origin. Assuming an initial planetary system like that described in Tsiganis et al., the planetesimal disk fulfilled the lifetime constraint discussed above only if its inner edge was located about 1 AU beyond the position of the last planet. With this kind of disk, the 1:2 resonance crossing event that destabilized the planetary system occurred at a time ranging from 192 My to 875 My. Modifying the planetary orbits also led to changes in the resonance crossing time, pushing it up to 1.1 Gy after the beginning of the simulation. This range of instability times well brackets the estimated date of the LHB from lunar data.

The top panel of Fig. 2 shows the giant planets' evolution in a representative simulation of Gomes et al. (2005). Initially, the giant planets migrated slowly due to the leakage of particles from the disk. This phase lasted 875 My, at which point Jupiter and Saturn crossed their 1:2 resonance. At the resonance crossing event, as

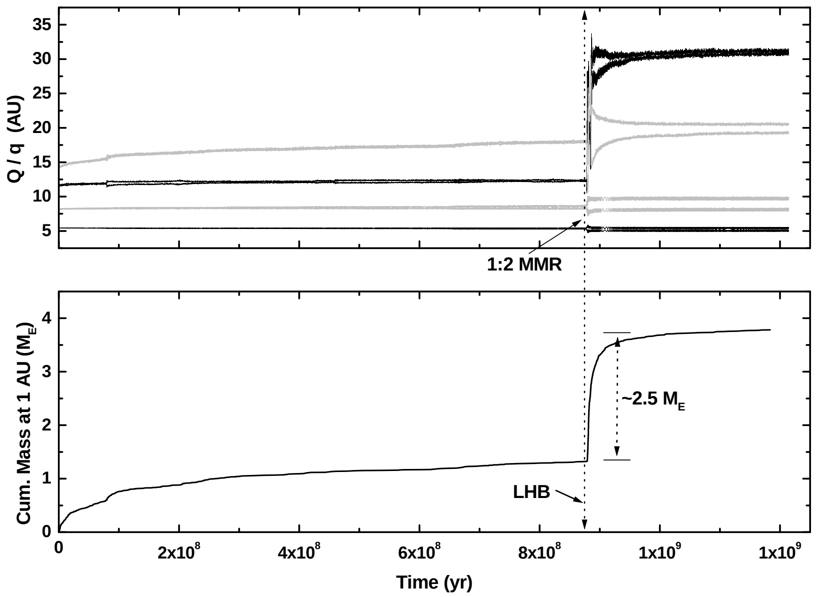

Figure 2: Planetary migration and the associated mass flux towards the inner Solar System from a representative simulation of Gomes et al., 2005. Top: the evolution of the 4 giant planets. Each planet is represented by a pair of curves - the aphelion and perihelion distances. In this simulation Jupiter and Saturn cross their 1:2 mean-motion resonance at 880 My. Bottom: the cumulative mass of comets (solid curve) and asteroids (dashed curve) accreted by the Moon. The comet curve is offset so that the value is zero at the time of 1:2 resonance crossing. The estimate of the total asteroidal contribution is very uncertain, but should be roughly of the same order of magnitude as the cometary contribution. However, it should occur over a longer time-span. From Gomes et al. (2005).

in Tsiganis et al. (2005), 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. Eventually they stabilized on orbits very similar to the current ones, at ∼20 and ∼30 AU respectively. The solid curve in the bottom panel shows the amount of material that struck the Moon as a function of time. The amount of material hitting the Moon after resonance crossing is consistent with the mass 6×10^{21}g (Levison et al., 2001) estimated from the number and size distribution of lunar basins that formed around the time of the LHB epoch.

However, the planetesimals from the distant disk -which can be identified as ‘comets’- were not the only ones to hit the terrestrial planets. The radial migration of Jupiter and Saturn forced secular resonances (resonances between the precession periods of the asteroids and the giant planets) to sweep across the asteroid belt, exciting the eccentricities and the inclinations of asteroids. The fraction of the main belt population that acquired planet-crossing eccentricities depends quite crucially on the orbital distribution that the belt had before the LHB, which is not well known. According to the simulations in O'brien et al., (2007), at the end of the terrestrial planet formation process, the asteroid belt should have had a dynamical excitation comparable, or slightly larger than the current one. In these conditions of orbital excitation, the secular resonance sweeping at the time of the LHB would have left ∼5-10% of the objects in the asteroid belt (Gomes, 2005). Still according to O'brien et al., the asteroid belt should have had, prior to the LHB, a mass of ∼10-20 times the current one. Thus, a depletion factor of ∼10% during the LHB is about right to justify the current mass of the belt. In this case, the total mass of the asteroids hitting the Moon was comparable to that of the comets (see Fig. 2). However, slight changes in the pre-LHB asteroid distribution, and the migration rate of Jupiter and Saturn (also highly variable from simulation to simulation, depending on the chaotic evolution of Neptune), can change this result for the asteroidal contribution to the Lunar cratering rate by a factor of several. In conclusion, the model in Gomes (2005) cannot state with confidence whether asteroids or comets dominated the impact flux on the terrestrial planets. What it can say, however, is that the asteroidal contribution came later and more slowly than the cometary contribution (see Fig. 2), possibly erasing much of the signature of the cometary bombardment.

The issue of which population dominated the impact rate can be solved by looking for constraints on the Moon. In Kring and Cohen (2002), analysis of Lunar impact melts indicated that at least one of the projectiles that hit the Moon, and probably more, had chemistry inconsistent with carbonaceous chondrites or comets. In Tagle (2005) it was found that the impact melt at the landing site of Apollo 17 was caused by a projectile of LL-chondritic composition. These results imply that the bombardment was dominated by asteroids typical of the inner belt.

In Strom and Neukum (1988), the comparison of size distributions of the craters formed at the time of the LHB on Mercury, Mars and the Moon allowed the calculation of the ratios of the impact velocities on these planets, leading to the conclusion that most projectiles had a semi-major axis between 1 and 2 AU. Comets never acquire such a small semi-major axis during their evolution, so this argument again favors a dominant contribution from the inner main belt. More recently, Strom et al. (2005) found that the crater size distribution on the lunar highlands is consistent with the size distribution of the asteroids currently observed in the main belt.

Taken altogether, these results point with little doubt to asteroids being the dominating (or, possibly, latest-arriving) projectile population for the terrestrial planets at the time of the LHB. However, they do not imply that the asteroids triggered the LHB. On the contrary, the remarkable match between the size distributions of craters and the main belt asteroids, pointed out in Strom et al. (2005), implies that -at the LHB time- asteroids were ejected from the main belt onto planet-crossing orbits in proportions independent of their size (unlike the current Near Earth Asteroids (NEAs) which, escaping from the belt due to size-dependent non-gravitational forces, have a size distribution significantly steeper than that of the main belt population). A size-independent ejection throughout the main belt could be due to sweeping of secular resonances due to giant planet migration, as in the Nice model, or the passage through the asteroid belt of a rogue planet, as we explain next.

4. AN ALTERNATIVE MODEL OF THE ORIGIN OF THE LHB

Chambers (2007) proposed an alternative model for the LHB, in which the Solar System initially contained a fifth terrestrial planet, Planet V, which became dynamically unstable after $\sim$ 700 My and was eventually removed. During the instability phase, this planet crossed repeatedly the asteroid belt, scattering a large fraction of its asteroid onto orbits that crossed that of the Earth, which caused the LHB. This scenario is supported by numerical simulations. In total Chambers performed 96 N-body simulations of the evolution of the 8 major planets with an additional body between Mars and the asteroid belt. In more than 1/4 of simulations, Planet V survived for 1 Gy. In most other cases, Planet V eventually collided with the Sun or hit another planet after several hundred Myr, leaving 4 surviving terrestrial planets. In 24/96 simulations, Planet V was lost by ejection or collision with the Sun while the other four terrestrial planets survived without undergoing a collision. In 18 cases, Planet V was removed at least 200 Myr after the beginning of the simulation, a good proxy for a late instability like that related to the LHB event. The instability time was found to depend on the initial aphelion distance of Mars. Reducing Mars's initial aphelion distance increases this time and also increases the fraction of systems surviving for 1 Gy.

The main discriminant aspect between this scenario and the Nice model is that in this case the LHB would have been exclusively due to asteroids and would have affected only the inner Solar System, whereas in the Nice model the LHB had a cometary component that affected also the outer Solar System.

There is observational evidence that some satellites of the giant planets underwent a heavy bombardment in the past, but it is unclear when this heavy bombardment occurred. An early heavy bombardment, due to the planetesimals scattered away from the giant planet region obviously would not be related to the LHB. Some indication on the chronology of the satellite bombardment may come from Iapetus, the most distant of the regular satellites of Saturn. A total of 14 basins have been estimated to be on Iapetus during the recent Cassini mission (Giese et al., 2008). The ejecta blanket of some of these basins overlap the equatorial ridge that gives to the satellite its characteristic UFO-like shape. So, they should have formed after the ridge. Thus, the question is when did the ridge form. According to models of the evolution of the shape of the satellite by Castillo et al. (2007), the ridge formed when the satellite despinned to synchronous rotation and this had to occur several hundred million years after the satellite formed. If this model is correct, then the heavy bombardment of Iapetus was late, and this supports the Nice model over the competitor model by Chambers. Moreover, the Nice model is consistent with the number of basins and smaller-size craters observed on Iapetus (Charnoz et al., 2008).

5. CONCLUSIONS

From the emerging view of the events that led to the origin of the LHB, it appears that the evolution of the Solar System was characterized by three main phases:

i) *the planetary accretion phase.* The giant planets formed within a few million years, in a compact orbital configuration embedded in a gas disk. The terrestrial planets presumably formed on a timescale of $\sim 10^8$ y (Touboul et al., 2007). Planetesimals formed out to a threshold distance of ∼30–35 AU. The asteroid belt underwent a first dynamical depletion and excitation during this phase (Petit et al., 2001), while planetesimals in the vicinity of the giant planets were removed, leaving a massive planetesimal disk only beyond the orbit of the outermost giant planet (Gomes, 2005).

ii) *a long quiescent phase* lasting around 600 My, during which the distant planetesimal disk was gradually eroded at its inner edge by planetary perturbations, leading to a slow migration of the giant planet orbits (Gomes, 2005).

iii) *the current phase*, which has lasted since 3.8 Gy ago, during which the Solar System has maintained essentially the same structure (Grieve and Shoemaker, 1994).

The LHB marks the cataclysmic transition between phase ii) and phase iii).

During this transition, the populations of small bodies of the Solar System resulted greatly affected. A fraction of the planetesimals in the original trans-Neptunian disk became trapped in the co-orbital regions of Jupiter (Morbidelli et al., 2005) and Neptune (Tsiganis et al., 2005), giving origin to the Trojan populations that we currently see. Planetesimals from the trans-Neptunian disk were presumably captured also in the outer asteroid belt (Levison et al., 2008a). As we have seen above, the asteroid belt was swept by secular resonances, and ∼90% of its pre-LHB objects were destabilized. Moreover, the capture of the irregular satellites of (at least) Saturn, Uranus and Neptune presumably occurred during the encounter phase among these planets (Nesvorny et al., 2007). Finally, the Kuiper belt acquired its current structure during the phase in which Neptune had a large eccentricity orbit and during its subsequent radial migration (Levison et al., 2008b).

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