A PLAUSIBLE CAUSE OF THE LATE HEAVY BOMBARDMENT

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Abstract. We show that at the end of the main accretional period of the terrestrial planets, a few percent of the initial planetesimal population in the 1–2 A.U zone is left on highly-inclined orbits in the inner solar system. The final depletion of this leftover population would cause an extended bombardment of all of the terrestrial planets, slowly decaying with a time scale of order 60 Ma. Because of the large impact velocities dictated by the high inclinations, these projectiles would produce craters much larger than those formed by asteroids of equal size on typical current Near-Earth asteroid orbits: on the Moon, basins could have been formed by bodies as small as 20 km in diameter, and 10 km craters could be produced by 400 m impactors. To account for the observed lunar crater record, the initial population of highly–inclined leftovers would need to be a few times that presently in the main asteroid belt, at all sizes, in agreement with the simulations of the primordial sculpting of both these populations. If a Terminal Lunar Cataclysm (a spike in the crater record ~ 3.9 Ga ago) really occurred on the Moon, it was not caused by the highly–inclined leftover population, because of the monotonic decay of the latter.

1. Introduction

After its formation about 4.5 Ga ago, the Moon's surface recorded a bombardment several orders of magnitude more intense than the current cratering rate, lasting almost a billion years. The high crater density on the older highland surfaces and the existence of huge impact basins testify to the existence of this heavy bombardment in the late phases of the Solar System's formation. A vast literature exists on this subject, and the reader can consult the recent papers by Neukum and Ivanov (1994) and Hartman et al. (2000) for detailed reviews.

It is now widely accepted that the population of lunar impactors was in heliocentric – rather than geocentric – orbit, because Mercury and Mars also show evidence of a primordial heavy bombardment and the relative size distribution of the craters on these planets is similar to that of the Moon (Strom and Neukum, 1988). Conversely, it is still heavily debated whether the period of intense bombardment was peaked near 4.0 to 3.8 Ga ago, or exponentially declined from 4.4 to 3.6 Ga ago. The first scenario is usually referred to as the *Terminal Lunar Cataclysm* (TLC); it was first proposed by Tera et al. (1974) to explain why the ages of the lunar rocks peak around -4.0 Ga and is also supported by the ages of the lunar basins, which seem to concentrate between -4.0 and -3.8 Ga (see Hartmann et al., 2000). The scenario of monotonic decrease in the bombardment rate during the ~ 1 Ga following planetary formation has been strongly advocated by Neukum and Ivanov (1994) and relies mostly on the increased density of craters measured on the highlands, which have been dated to be 4.35 Ga old (Neukum, 1983). We will refer to it in the following as the *Exponentially Decaying Bombardment* (EDB). In that scenario the concentration of the rock ages at around -4.0 Ga is just an effect of the resetting of radiometric clocks due to the previously heavier bombardment (Grinspoon, 1989). The same phenomenon could also influence basin dating, but the ability of impacts to reset clocks in such a general fashion is debatable (see Hartmann et al., 2000). It has also been argued that Imbrium ejecta are much more pervasive than generally assumed, so that most of the ages assigned to the other basins, in the narrow "cataclysm" age range, actually refer to Imbrium (Haskin, 1998).

In principle, the two scenarios are *not* mutually exclusive: one could imagine a TLC spike superposed on an EDB background. However, there is no general consensus on what could cause the Late Heavy Bombardment (LHB) in either its possible forms (TLC or EDB). Hypotheses range from leftovers of terrestrial planet accretion, to main belt asteroids, to comets.

Wetherill (1975, 1977) was the first to investigate the possibility that the LHB is simply the tail of the accretion process of the terrestrial planets, with Monte Carlo simulations. The timescales that he found were compatible with the EDB scenario. However, it is now known (Dones et al., 1999a) that Monte Carlo simulations in some cases may be not quantitatively accurate, because they do not take into account resonant effects. The current view is that the leftovers of planetary accretion should have a dynamical behavior similar to that of the current Near–Earth Asteroids; the latter have a median dynamical lifetime of only 10 Ma, so that the heavy bombardment would not last long enough (Gladman et al., 1996, 1997, 2000).

Looking for a population of long-living bodies in the inner Solar System, Dones et al. (1999b) showed that a population of objects initially on circular coplanar orbits between Venus and Mars decays with a median lifetime of several 10^7 a, and extrapolated that about 10% of the bodies would survive for 600 Ma. This population would therefore have a dynamical lifetime compatible with the LHB. However, it is questionable that such a dynamically cold population would exist at the end of terrestrial planet accretion. The prevailing opinion is that a rapid ($< 10^6$ a) process of runaway growth led to the formation of many "planetary embryos" with lunar to martian masses (see references in *Accretion of the terrestrial planets*); the terrestrial planets then formed on a longer time-scale (several 10^7–10^8 a) by the high–velocity mutual collisions of these embryos (Wetherill, 1992; Chambers and Wetherill, 1998; Agnor et al., 1999). Petit et al. (1999b, 2000) showed that, in this process, any population of small bodies would inevitably be strongly and rapidly dynamically excited, so that it is very implausible that a significant number of objects could persist with $e \sim i \sim 0$.

The asteroid belt is the main reservoir that keeps the current population of Near Earth Asteroids in a rough steady state (Bottke et al., 2000). An expected smooth mass distribution in the proto-solar disk implies a primordial asteroid belt $\sim 10^3$ times more massive than the present one (Weidenshilling, 1977). The production of NEAs, resulting from the collisional activity in the asteroid belt, should scale as the square of the number of asteroids in the belt. Thus, during the period when the asteroid belt was massive the NEA production rate should have been some 10^6 times higher than at present, causing a heavy bombardment on all terrestrial planets. The trouble with this scenario is that the primordial asteroid belt must have lost most of its bodies very rapidly to prevent the destruction of the fragile basaltic crust of Vesta (Davis et al., 1995; Burbine et al., 1996), implying that the phase of massive NEA production could not have lasted for several 10^8 a. The same constraint argues against a scenario where the excitation and depletion of the primordial asteroid belt is delayed for several hundred Ma, so as to cause a Terminal Lunar Cataclysm (as proposed in Levison et al., 2000b; see also Zappalá et al., 1997). The recent simulations by Petit et al. (1999b, 2000) suggest that the asteroid belt was excited and depleted well before the terrestrial planets completed their growth process, consistent with the constraint given by Vesta; this seems to exclude the main belt from causing either the Exponentially Decaying Bombardment or the Terminal Lunar Cataclysm.

Relating the LHB to the origin of water on Earth, Chyba (1990, 1991) claimed that the comets would constitute the main projectile population. However, quantitative numerical integrations show that the "cometesimals" in the Jupiter–Saturn zone should have been ejected from the Solar System in the first few Ma after the formation of these giant planets, *i.e.* well before the formation of the Earth and the Moon (see Morbidelli et al., 2000 for a discussion). Only cometesimals initially in the trans–Neptunian region could have produced a flux of projectiles in the inner Solar System that slowly decayed with a median lifetime of ~ 100 Ma, compatible with the Exponentially Decaying Bombardment time-scale (Duncan and Levison, 1997). A late formation of Uranus and Neptune could delay the beginning of this cometary shower, thus potentially also making it compatible with a Terminal Lunar Cataclysm scenario (Levison et al., 2000b). At least 40,000 craters larger than 10 km should have been formed during the LHB (see sect. 3). The collision probability with the Earth of a cometesimal initially in the outer solar system is of order 10^{-6} (Levison et al., 2000a); the collision probability with the Moon is about 20 times lower. This implies that, to cause the LHB, the primordial population of cometesimals in the outer solar system needed to contain of order 10^{12} kilometer–sized bodies. The constraints being very weak, the existence of this population cannot be ruled out *a priori*. However, the heavily cratered surfaces of Jupiter's satellites Callisto and Ganymede show a crater population very different from that of the terrestrial planets, the former being characterized by a paucity of large craters ($D > 40$ km) and an overabundance of small craters ($D < 20$ km); according to Strom and Neukum (1988), this argues that the population responsible for the LHB was not on Jupiter–crossing orbit, apparently ruling out the role of comets.

In conclusion, none of the above quoted scenarios for the heavy cratering of planetary surfaces is completely satisfactory.

In this paper, we revisit the scenario involving the leftovers of planetary accretion, in the framework of a modern model of formation of terrestrial planets. In *Accretion of the terrestrial planets* we review the current general model for the accretion of the Earth and we follow the dynamical evolution of leftover planetesimals. Having determined what fraction of the these planetesimals is dynamically long–lived and their typical orbital distribution, in *Simulation of the Late Heavy Bombardment* we compute the time evolution of their collision rate with the terrestrial planets and the impact velocities. In *Comparison with Crater Data* we evaluate our results with respect to the crater record on the Moon and compute the total number of bodies of various sizes that would be required in order to account for the number of impacts, estimated to have occurred during the LHB. We finally discuss the advantages of this new scenario as well as the major open questions.

2. Accretion of the terrestrial planets

It is now generally accepted that in the inner solar system the process of runaway growth ended with the formation of many "planetary embryos" of lunar to martian mass (Greenberg et al., 1978; Wetherill and Stewart, 1989, 1993; Ida and Makino, 1993; Namuoni et al., 1996; Weidenschilling et al., 1997). The formation of the terrestrial planets then proceeded by high–velocity collisions of these planetary embryos. The availability of new symplectic integration algorithms that are able to handle close encounters between massive bodies (Duncan et al., 1998; Chambers, 1999) and the spectacular improvement of computer speeds have recently allowed detailed simulations of this second phase of terrestrial planet accretion. Chambers and Wetherill (1998) and Agnor et al. (1999) have shown that terrestrial planets are eventually formed on a timescale of several 10^7 to 10^8 years; in addition, Chambers and Wetherill (1998) showed that if planetary embryos originally existed in the asteroid belt, they would have been dynamically removed from the 2–4 AU region.

This scenario has several merits. First, the timescale of accretion of the terrestrial planets is well consistent with the datation of the formation and differentiation of the Moon and of the differentiation of the Earth's core, given by cosmochemical studies (Lee et al., 1997; Allègre et al., 1995). Second, the primordial existence of planetary embryos in the asteroid belt would explain the prently observed mass depletion and dynamical excitation (Petit et al., 1999b, 2000). Third, the accretion by the forming Earth of a planetary embryo originally formed in the outer asteroid belt seems to be the most plausible scenario for the origin of the water on our planet (Morbidelli et al., 2000).

However, not everything in the simulations is fully consistent with the present architecture of our planetary system. The final eccentricities and inclinations of the accreted planets are much larger than those observed. This is probably a consequence of the fact that these simulations do not include a large population of small bodies, carrying a non–negligible total mass, which could damp the final eccentricities and inclinations of the terrestrial planets by dynamical friction (see Hamilton, 1998 for discussion). As a result of the large eccentricities, in many cases only two terrestrial planets are produced at the end of the simulations. Finally, the planet formed in the 1.5-2 AU zone typically has a mass much larger than that of the real Mars, although smaller than that of the Earth. Despite these limitations, these simulations of terrestrial–planet accretion are still valuable to explore several aspects of the primordial evolution of the inner Solar System.

To understand the orbital distribution of planetesimals that survive the main stages of planetary accretion, we integrate the evolution of 100 test particles initially placed between 1 and 2 AU, in the framework of one of the simulations of terrestrial planet formation by Chambers and Wetherill (1998). The integration is done using a version of the SWIFT_RMSV3 code (Levison and Duncan 1994), modified by Petit et al. (1999a) to interpolate the evolution of the orbits of the giant planets and of the embryos, given in a previously computed file.

Fig. 1 shows snapshots of the semimajor axis and inclination distribution of the system. The particles rapidly acquire large orbital inclinations, while their total number decays because of collisions with the Sun and with the planetary embryos. After 50 Ma, 10% of the test particles survive, with a median inclination of ~ 45 degrees. At the end of the 100 Ma–simulation (not shown in Fig. 1) 3% of the test particles survive; all have $i > 39$ degrees and $a < 2$ AU.

To check the variability of the results on the initial mass distribution of the embryos, we also integrate the evolution of test particles initially placed between 1.5 and 2 AU in the framework of a second model (Chambers, unpublished data) that assumes the existence of embryos only outside 1.5 AU, with small initial mass (twice that of the Moon). This model fails to generate Earth–mass planets in the terrestrial-planet region and thus likely provides a lower limit for the number and masses of the planetary embryos and, consequently, on the amount of dynamical excitation that occurred in the inner solar system. Nevertheless, the evolution of the test particles in this "lower limit" model is qualitatively similar to that shown in Fig. 1, with most of the survivors staying on orbits with more moderate, but still large, inclinations (the median value being 27 degrees). We conclude that the existence of highly–inclined leftover bodies is a robust consequence of planet formation. Their inclinations are much larger than those of the vast majority of NEAs (Bottke et al., 2000), suggesting that they have much longer dynamical lifetimes.

One could object that these results on small–body orbital excitation cannot be trusted because the resulting inclinations of the final planets are too large (see the last panel of Fig. 1). But, as discussed above, it is likely that the inclinations and eccentricities of the planets have been damped by dynamical friction, a phenomenon not acting on small bodies. On the contrary, the dynamical excitation of the small–body orbits could even be enhanced by dynamical friction (Kokubo and Ida, 1996).

3. Simulation of the Late Heavy Bombardment

To study the subsequent evolution of the highly–inclined leftover bodies and to investigate their possible relationship with the Late Heavy Bombardment, we need to start from a large statistical sample. For this purpose, we "clone" the particles surviving at the end of the simulation shown in Fig. 1 using the following procedure. We divide the (q, Q, i)–space (q and Q being the perihelion and aphelion distances, respectively) in cells and compute the total time spent in each cell by the surviving particles during the last few million years of the integration. This normalized *residence time* distribution can be regarded as the probability distribution of the leftover particles in the (q, Q, i)–space. We then generate 200 test particles according to this distribution; their angles M, ω, ϖ (mean anomaly, argument and longitude of perihelion) are set at random, as well as the exact values of q, Q, i inside each cell. The left panels of Fig. 2 show the resulting (a, e) and (a, i) distribution.

We use the same procedure also to generate 200 “clones” of the surviving particles in the “lower–limit” model mentioned in the previous section. The resulting distribution is shown in the right panels of Fig. 2. Notice that in this case the particles are much less dispersed because of the reduced scattering resulting from the smaller embryos’ masses. In the following, we will refer to the distribution on the left of Fig. 2 as MODEL 1 (our reference case) and to that on the right as MODEL 2 (an extreme case to check the robustness of our results).

The dynamical evolution of the particles is then numerically integrated for 100 Ma using the swift–rmvs3 integrator (Levison and Duncan, 1994), with a timestep of 7.5 days. Being interested in the evolution of these bodies *after* the completion of planetary accretion, we adopt the current masses and orbital configuration of the planets as initial conditions. The particles are eliminated from the simulation when they impact the Sun or a planet or are ejected from the Solar System.

The top panel of Fig. 3 shows the fraction of the integrated particles that are still ’active’ in the simulation, as a function of time. The bodies in MODEL 1 (crosses) and MODEL 2 (circles) behave very similarly: after a rapid drop in the first 10 Ma, the decay of the population slows, with a median lifetime of order 50–60 Ma. For reference, a curve of exponential decay $N \propto \exp(-t/77)$ (t expressed in Ma) is also plotted, which is an eyeball fit to the decay of the population of MODEL 1 in the 10–100 Ma range. This slow decay is consistent with having chosen a population that mimics the orbital distribution of the particles that survived for 100 Ma in the terrestrial planet formation simulation (see previous section). A continuation of the simulation of MODEL 1 shows that 8 particles (4% of the population) are still 'active' after 300 Ma. The 'faster' drop over the first 10 Ma may be an artifact introduced by the resetting of the planetary system: a fraction of the particles ($\sim 15\%$) that were long–lived within the planetary system generated in the simulation of Fig. 1 become short–lived in the framework of the present planetary configuration.

The typical end-states of the particles of MODEL 1 are: collision with the Sun (47%), collision with a terrestrial planet (27%), and ejection from the Solar System (1%). The numbers for MODEL 2 are comparable. Interestingly, while the Sun-grazing fraction is similar to that of current near-Earth asteroids (Gladman et al. 2000), the fraction that strikes a planet is about a factor of 2 higher, and about an order of magnitude fewer are ejected. This is likely due to the higher initial inclinations in the present simulation; due to their large relative velocities, the small bodies are not easily transported to large semimajor axis by encounters with the terrestrial planets, and therefore have little chance to reach Jupiter and be ejected from the Solar System.

Once the simulation is completed, we compute the time evolution of the collision probability that the particle population has with the Moon and the other planets, as follows. Our numerical simulation records the orbital elements $(a, e, i)(t, n)$ as a function of time t at 5000 year intervals for each of the N particles ($n = 1, \ldots, N$), as well as for the planets (the Moon is taken to have the same heliocentric orbital elements as the Earth). For every $(a, e, i)(t, n)$ the differential collision probability with a given planet $p(t, n)$ and the relative impact velocity $v(t, n)$ are computed, averaging over all possible orbital configurations occurring during a precessional cycle of the orbits, and taking into account the gravitational focusing of the considered planet. This procedure has been accomplished following Wetherill (1967), and using a numerical code implemented by P. Farinella and D. Davis (1992) and kindly provided to us. The collision probability of the particle population at time t, normalized over the initial number of integrated particles, is then $P(t) = \sum_n p(t, n)dt/N$, and the weighted mean impact velocity is $V(t) = \sum_n p(t, n)v(t, n)/(NP(t))$. Finally, $P(t)$ and $V(t)$ are averaged over 1 Ma time intervals.

Some concern over this procedure might be merited in light of the high inclination of the particle population. It is well known that at high i the motion of the argument of perihelion is highly non–linear in time (ω may even librate), which is associated with large coupled oscillations of e and i (Kozai, 1962). The Farinella and Davis procedure assumes a linear precession of the angles, at constant e and i. To check the statistical accuracy of our procedure on the ensemble of the particle population, we compute the cumulative collision probability $P_c = \int_0^{100\mathrm{Ma}} P(t)dt$ with Venus, the Earth and Mars, and compare the results with the fraction of the particle population that actually impacted the planets during the simulation. The resulting values of P_c are 10.1%, 5.9% and 0.6% for Venus, Earth and Mars respectively, while the corresponding numbers coming from the simulation are 12.5%, 13.0% and 1.5%. We conclude that this method for computing the collision probability is correct (at least for a large population of particles) within a factor of 2, with a tendency to underestimate (Dones et al. 1999a, Gladman et al. 2000).

The middle panel of Fig. 3 shows $P(t)$ for lunar impacts under MODEL 1 and MODEL 2. The vertical scale should be interpreted as the mean collision probability per million years per particle initially in the population. The curve of the equation $P \propto \exp(-t/77)$ is plotted again for reference, which nicely mimics the decay of the collision probability of the population over the 10-100 Ma interval, which implies that the collision probability *per surviving particle* stays roughly constant with time at $\sim 8 \times 10^{-5}$/Ma.

The bottom panel of Fig. 3 shows the mean impact velocity $V(t)$, still for the Moon. The bodies of MODEL 1 impact at about 30km/sec, an unusually high speed compared to those of NEAs (~10–15 km/sec; Gladman et al. 2000) and Jupiter–family comets (20 km/sec; Shoemaker et al. 1994). The bodies of MODEL 2 impact the Moon with a more moderate speed of 22–

25km/sec, because of their smaller mean inclination. $V(t)$ slowly grows with time because of a weak correlation between the lifetime of the bodies and their mean inclination.

The differential and cumulative distribution of the impact velocities on the Moon, resulting from the simulations of MODEL 1, is shown in Fig. 4. Note that about 50% of the impacts occur with a speed greater than 30km/s. The cumulative distributions of the impact velocities on Mercury, Venus and Mars are also shown, for comparison.

4. Comparison with crater data

We now have all the elements that we need to compare the results of our simulations with the crater record on the Moon and the other planets.

According to Neukum and Ivanov (1994), the crater record on the Moon indicates that the flux of projectiles during the EDB decreased proportionally to $\exp(-t/144)$, with t expressed in Ma. According to Hartman et al. (2000), in the interval 4.4-3.9 Ga ago the flux of impactors decayed on average as $\exp(-t/56)$. In our model (Fig. 3, middle panel) the collision rate of the highly–inclined leftover population decays as $\exp(-t/77)$. The decay rate of our model population therefore seems to be slow enough to be comparable with the crater record, within the uncertainties of the latter.

Beyond matching the gross timescale, we need to estimate the number of objects of various sizes that our highly–inclined population should initially have had in order to be compatible with the crater record. According to Fig. 16 of Neukum and Ivanov (1994), the number of craters with diameter $D > 10$ km formed on the Moon between 4.4 and 3.9 Ga ago is 10^{-3} per square kilometer. Integrating over the surface of the Moon gives 40,000 craters. This is probably only a lower estimate of the total number of 10 km craters formed in the -4.4 to -3.9 Ga period, because the crater record on the lunar highlands is saturated (Chapman and McKinnon, 1986). By extrapolating the curve plotted in the middle panel of Fig. 3 to 500 Ma and integrating it over the 0-500 Ma interval, we obtain a *cumulative* collision probability of 5×10^{-3} per particle initially in the population; that is, 0.5% of the initial particles will eventually strike the Moon. This implies that the population of highly–inclined leftovers had to initially contain 8×10^{6} bodies potentially capable of excavating a 10 km crater on the Moon. To compute the required size of these bodies, we apply the "Pi–scaling method" (Melosh, 1989, Chapter 7), using a code implemented by J. Melosh. As a lower limit, we assume that the bodies have a density ~ 2.5 g/cm^3, because our highly–inclined leftovers were initially in the inner solar system, so that they should not be very different from S–type asteroids. We assume a target density of 3.3 g/cm^3, a competent rock composition (suitable for the Moon), and an average impact angle of 45 degrees. Moreover we adopt the scaling law $D = 1.17 D_{TR}$ between the diameter D of the observed crater and the diameter D_{TR} of the transient crater, given by McKinnon et al. (1997) for craters with transient diameter smaller than a threshold D_{SC} (about 15 km for the Moon) that marks the transition between simple and complex crater-forms. With these parameters we obtain that at 30 km/sec (suitable for the MODEL 1 population) the minimal projectile size required to form a 10 km crater on the Moon is 400 m, while at 25 km/sec (suitable for MODEL 2) it is 450 m. Therefore, we conclude that the highly–inclined leftover population needed to have originally contained at least $\sim 10^7$ bodies larger than 400m. For comparison, the total number of asteroids larger than 400m in the main belt is estimated to be $\sim 4 \times 10^6$ (Jedicke and Metcalfe, 1998; Durda et al., 1998). This ratio between the original highly–inclined leftover population and the current main belt population is consistent with the results of the simulations of their primordial sculpting. In fact, in *Accretion of the terrestrial planets* we found that the highly–inclined leftover population would include 3–10% of the population of planetesimals originally between 1 and 2 AU, while Petit et al. (2000) found that only 0.7% of the asteroids originally in the 2–4 AU region should have remained in the asteroid belt. Assuming roughly equal masses in the 1–2 and in the 2–4 AU regions (as it would be for a disk surface density decreasing as the square of the heliocentric distance), we estimate –independently from the lunar crater record– that the highly–inclined leftovers could constitute a population which was 5-10 times more numerous than the entire current main belt population.

A similar computation can be applied to the number of lunar basins.

The basins are defined as the "craters" larger than 300km, and their total number on the Moon's surface is between 28 and 45 (Wilhelms et al., 1987). We compute the minimal size of a basin–forming impactor as follows. We first use the scaling law $D = 1.17 D_{TR}^{1.13} / D_{SC}^{0.13}$ between the final diameter D and the transient diameter D_{TR}, as given by McKinnon et al. (1997) for craters with transient diameter larger than D_{SC}. We thus obtain that the transient diameter of a basin with $D = 300$ km should be 180–190 km. Then, using this number, following the Pi–scaling method again and assuming the same values detailed above for the other parameters involved in the computation, we find that an impactor diameter of 20 km is enough to form a 300 km basin. Moreover, according to the kinetic energies estimated by Zahnle and Sleep (1997), only 4 basins (Imbrium, Crisium, Orientale and the South Pole–Aitken) would require projectiles larger than 50 km in diameter (several other basins are just below the 50 km threshold). Therefore, based on a cumulative collision probability of 5×10^{-3} per particle, the highly–inclined leftover population had to initially contain about $\sim 10^4$ bodies larger than 20 km and $\sim$ 1000 larger than 50 km. In comparison, the corresponding numbers for the present-day asteroid belt are 2000 and 500 respectively (Durda et al., 1998).

Up to now we have compared our results only with the crater record on the Moon. The crater records on Mercury and Mars may also provide useful information. Strom and Neukum (1988) noted that the crater size-frequency distributions for the highlands of Mercury, the Moon, and Mars have similar shapes. The three curves have bumps at slightly different sizes. Strom and Neukum interpreted this trend as the result of a common population of heliocentric impactors striking all three bodies, with the highest impact velocity occurring on Mercury and the lowest on Mars. Using a Holsapple-Schmidt (1982) scaling law modified for complex craters, they inferred that the Mercury/Moon impact velocity ratio lay in the range 1.37 – 2.18, while the Mars/Moon ratio was 0.48 – 0.68. The simulations of MODEL 1 give a Mercury/Moon impact velocity ratio of 1.66 and a Mars/Moon ratio of 0.8. This agreement is good considering the simplicity of our basic model. Note that it is plausible, from the Petit et al. (2000) simulations, that the asteroid-belt excitation process left behind a population of Mars–crossing bodies not included in our simulation. These bodies would also have a median lifetime of order 100 Ma (Michel et al., 2000), would preferentially impact Mars (with a low relative velocity), and thus reduce the total Mars/Moon impact velocity ratio.

The crater size-frequency distributions of the old surfaces of the Galilean satellites is very different from that of the terrestrial planets, leading Neukum and Strom to conclude that the projectile population that caused the LHB in the inner solar system was not crossing Jupiter's orbit. This is precisely what happens in our simulations, where only 1% of the original population becomes Jupiter–crossing. On the other hand, the surfaces of the Galilean satellites may be younger than 3.8 Gyr (Zahnle et al, 1998), and thus not record the LHB in any case.

5. Discussion

We have presented a plausible explanation for an exponentially decaying Late Heavy Bombardment. The major strength of our model is that it is not ad hoc, being an extension of a general model that accounts for the origin of the terrestrial planets (Chambers and Wetherill, 1998; Agnor et al., 1999), the delivery of water and volatiles on Earth (Morbidelli et al., 2000) and the primordial depletion and excitation of the asteroid belt (Petit et al., 1999b, 2000).

We have shown that:

1) the time-decay of the highly–inclined leftover population is consistent with the exponential decrease of the crater density with the age of the lunar terrains, within the uncertainties of the crater record.

2) the initial number of bodies in the highly–inclined leftover population required to cause the LHB is reasonable. The initial population should have contained a few times as many objects as the present asteroid belt, in each size range, consistent with the simulations of their primordial sculpting.

3) only $\sim 1\%$ of the highly–inclined leftover bodies eventually reach the

orbit of Jupiter, which may explain why the crater size-distribution on the heavily cratered surfaces of the Galilean satellites is different from that of the terrestrial planets.

4) the Mercury/Moon and Mars/Moon impact-velocity ratios of the highly–inclined leftover population are similar to the values computed by Strom and Neukum (1988).

An additional appealing point is that, because of the large impact velocity (~ 30 km/sec), the projectile sizes for forming the lunar basins are moderate. In our model, only 50 bodies larger than 20 km in diameter impacted the Moon during the LHB, and only 4 of them were bigger than 50 km. We repeat that these results have been achieved under the conservative assumption that the projectiles density was 2.5 g/cm^3 (partially differentiated planetesimals in the inner solar system could easily have higher densities) and using a method for computing the planetary collision probabilities that seems to slightly underestimate the real impact rates.

This model does not provide a mechanism to produce a Terminal Lunar Cataclysm (which, as discussed in the introduction, is not unanimously accepted). The existence of small spikes in the cratering rate is allowed, because of the stochastic nature of the bombardment process but, on average, our model predicts the collision rate on the planets would monotonically decrease with time. In a normal power-law size distribution, due to their relative under-abundance the impacts of the largest projectiles should mostly occur in the early epochs, while the tail of small impacts continues for a much longer time. Therefore our model cannot produce basins predominantly in the so–called Nectarian period (3.9-3.8 Ga ago), relative to earlier epochs.

We stress that the existence of a non-negligible population of highly-inclined leftovers is a byproduct of the accretion process of the terrestrial planets that cannot easily be avoided. Therefore, if a Terminal Lunar Cataclysm really occurred, it should have come on top of a slowly decreasing cratering rate caused by this population.

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Figure captions

Fig. 1 Snapshots of the orbital distribution of the asteroids and of planetary embryos in our reference simulation. Small bodies are denoted by asterisks or crosses, depending on their initial semimajor axis. The embryos are denoted by open circles, whose radius is linearly proportional to their mass. Their evolution is taken from Chambers and Wetherill (1998). Full–mass Jupiter and Saturn exist at the beginning of the simulation. Notice how the population of small bodies rapidly decays in number and acquires a large mean inclination. The excitation of the eccentricities (not shown in the plot) is comparably large. At the end of the simulation, at 100 Ma, only 3% of the small bodies survive, all at large inclinations. Two terrestrial planets are left, in a stable configuration. The largest planet has a mass of 1.39 $M_{\oplus}$ with a semimajor axis of 0.7 AU; the smaller has Mars' semimajor axis, but a large inclination, and half an Earth mass.

Fig. 2 The initial conditions of the test particles that trace the orbital distributions of the leftover planetesimal population found in the simulations of accretion of terresrial planets (see text). The left panels refer to the simulation of Fig. 1 (MODEL 1), while the right panels refer to the "lower limit" simulation, carried out within a pessimistic model of the primordial distribution of protoplanetary embryos (MODEL 2). Inclination is in degrees.

Fig. 3 Top panel: the fraction $F(t)$ of the planetesimal population that survives as a function of time. Middle panel: the time evolution of the collision probability $P(t)$ with the Moon; the scale on the y–axis gives the collision probability per million years per particle initially in the population. Bottom panel: the time evolution of the mean impact velocity on the Moon. Crosses refer to the simulation of MODEL 1 and open circles to that of MODEL 2. The reference curve in the top and middle panels is only to guide the eye, and has equation $y \propto \exp(-t/77)$ with arbtirary amplitude.

Fig. 4 Top panel: The cumulative distribution of impact velocities (relative frequency of impacts with velocity larger than v) for the Moon (bold solid), Mars (long dash), Venus (light solid) and Mercury (dotted). Gravitational focussing has been taken into acocunt. Bottom panel: the Moon's differential distribution of impact velocities (relative frequency of impacts with velocity between v and $v + 1$km). The calculations for both panels are based on the integrations of MODEL 1.

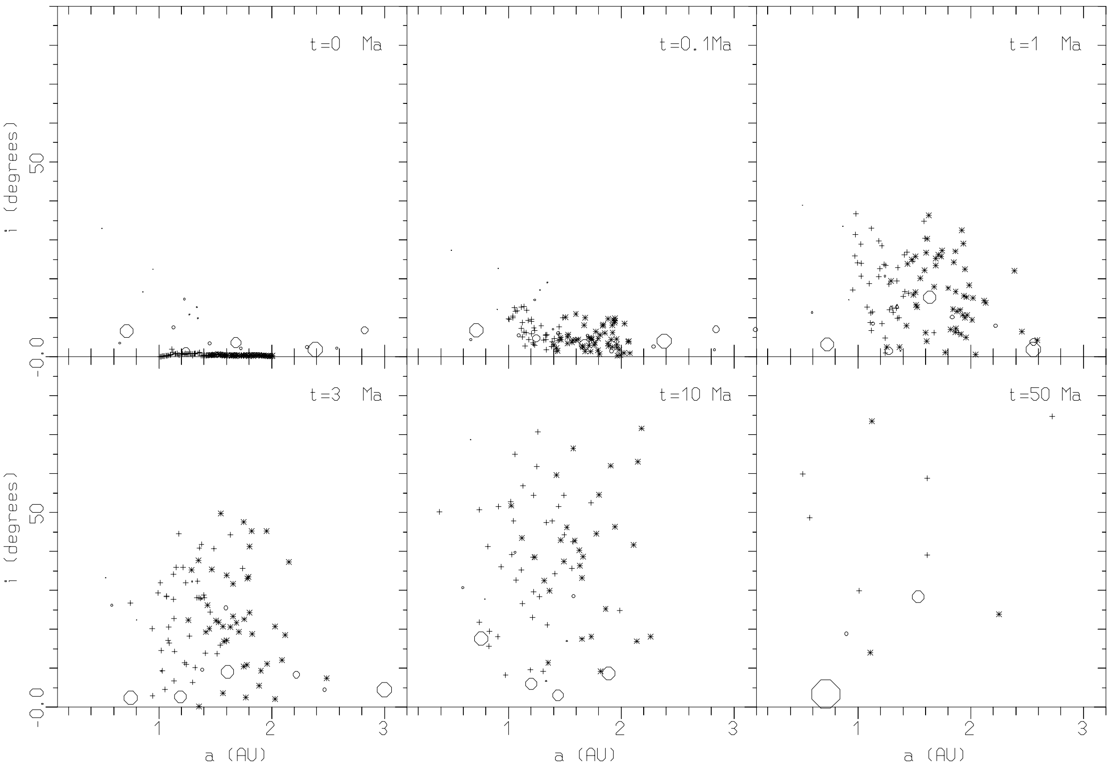


Fig. 1.

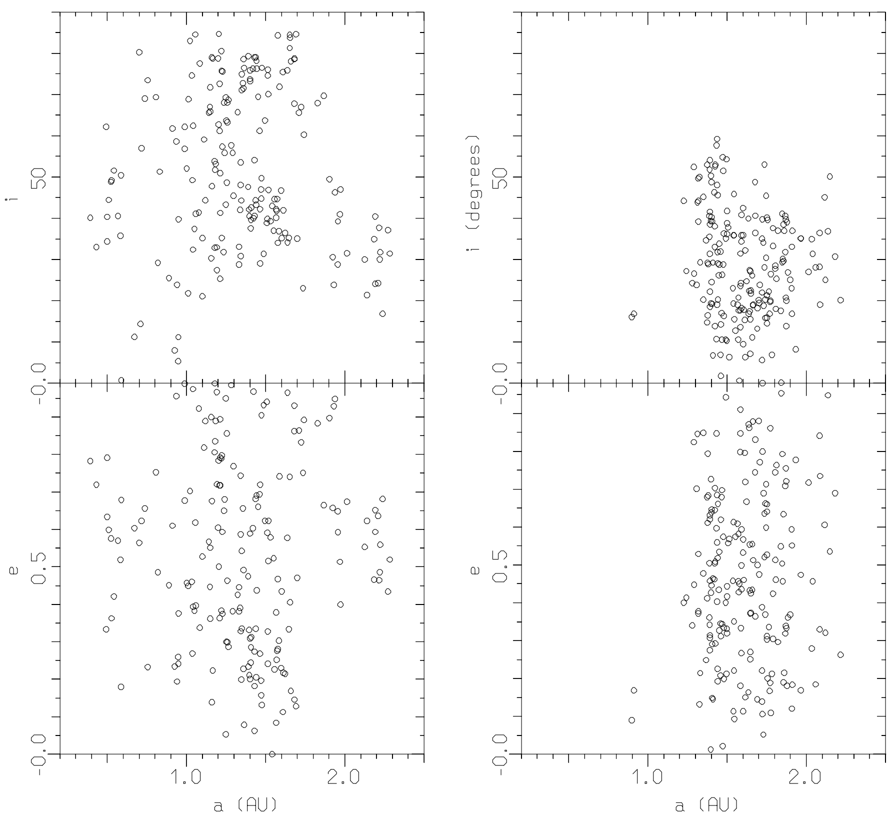


Fig. 2.

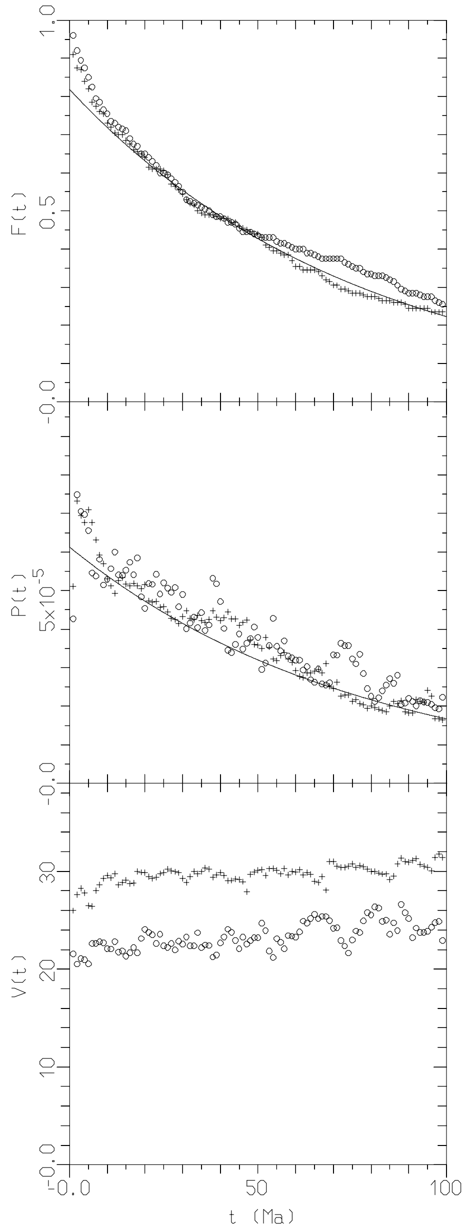
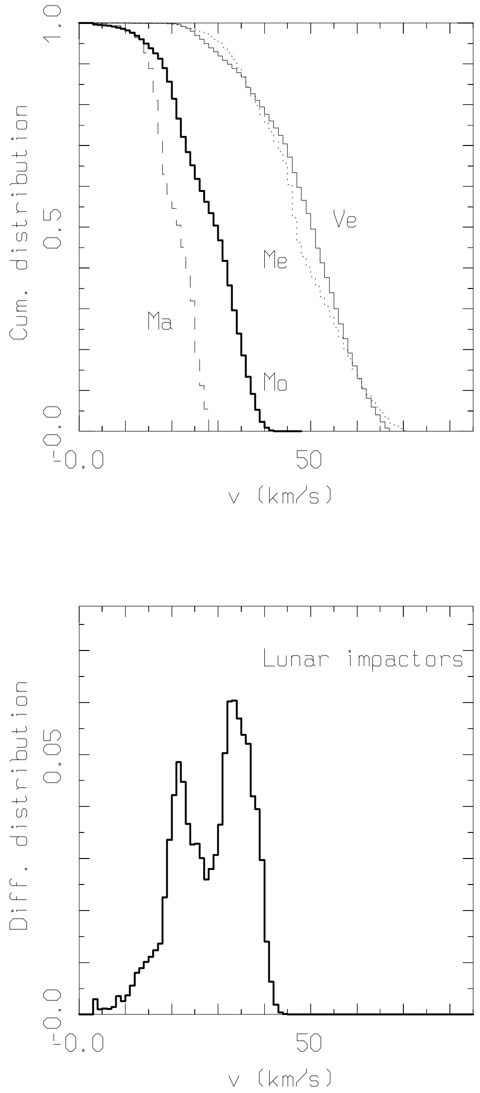


Fig. 3.



1.0
0.5
0.0
-0.0
50
Cum. distribution
v (km/s)
Ve
Me
Ma
Mo
Lunar impactors
Diff. distribution
0.05
0.0
-0.0
50
v (km/s)

Fig. 4.