A PLAUSIBLE CAUSE OF THE LATE HEAVY BOMBARDMENT

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Abstract. At the end of the main accretional period of the terrestrial planets, a few percent of the initial planetesimal population is left on highly-inclined orbits in the inner solar system (Petit et al., 2000). We show that this 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 would 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, consistent with the Petit et al. (2000) estimate for this population. If a Terminal Lunar Cataclysm (a spike in the cratering record ~ 3.9 Ga ago) really occurred on the Moon, it was not caused by the highly–inclined leftover population, because of the monotonic diminishment of the latter.

1. Introduction

After its formation at about 4.5 Ga ago, the Moon's surface records 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 for 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 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 the same as on the Moon (Strom and Neukum, 1988). Conversely, it is still intensely debated whether the period of intense bombardment was peaked at 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 of the bombardment rate during $\sim$ 1 Ga after planetary formation has been strongly advocated by Neukum and Ivanov (1994) and relies mostly on the high over-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 have 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 is also argued that the Imbrium ejecta materials 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, that 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 caused the Late Heavy Bombardment (LHB) in either its possible forms of TLC or EDB. Hypotheses range from leftovers of terrestrial planet accretion, to main belt asteroids, to comets.

Wetherill (1975, 1977) first investigated the possibility that the LHB is simply the tail of the accretion process of the terrestrial planets. In principle, the leftover of planetary accretion should have a dynamical behavior similar to that of the current Near Earth Asteroids; the latter having a median

dynamical lifetime of only 10 Ma (Gladman et al., 1997, 2000), so that it is reasonable to expect that the heavy bombardment would not last long enough.

Looking for a population of long-living bodies in the inner Solar System, Dones et al. (1999) 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 if such a dynamically cold population would exist at the end of terrestrial planets 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 (Greenberg et al., 1978; Wetherill and Stewart, 1989, 1993; Ida and Makino, 1993; Namuoni et al., 1996; Weidenschilling et al., 1997); the terrestrial planets then formed on a longer time-scale (several 10^7–10^8 a) by the highly–velocity mutual collisions of these embryos (Wetherill, 1992; Chambers and Wetherill, 1998; Agnor et al., 1999). These time scales are comparable to those provided by geochemical studies, which date formation and differentiation of the Moon (Lee et al., 1997). Petit et al. (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 protosolar disk implies a primordial asteroid belt $\sim 10^3$ times more massive than the present one (Weidenshilling, 1977). The production of NEAs, being the outcome of 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 (levison et al., 2000b). The recent simulations by Petit et al. (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 with the origin of water on Earth, Chyba (1990, 1991) claimed that the comets have constituted 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 (Morbidelli et al. 2000). 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 $\sim$ 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). About 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 should have contained 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 Ganymed 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. However, the results by Petit et al. (2000) suggest a new scenario for the origin of the LHB, which is in fact a variant of the classical one invoking the leftovers of planetary accretion. In the Petit et al. simulations a fraction of the population of small bodies in the inner solar system was observed to survive the long ($\sim$ 100 Ma) phase during which the terrestrial planets accrete from numerous massive planetary embryos. The surviving bodies are all found, due to the scattering off of the planetary embryos, on orbits with large inclination and large eccentricity (much larger than those typical of Near Earth Asteroids). These orbits are ultimately unstable, because they cross those of the terrestrial planets, but the high relative velocities that result from the very large orbital inclinations reduce the destabilizing effect of planetary encounters. As a consequence, these highly–inclined leftovers of planetary accretion constitute a population that is dynamically long–lived. Because of the high inclinations, the collision probability with the Earth of each individual body is expected to be small; but this might be compensated by the total number of bodies,

which is potentially very large. In fact, in Petit et al. simulations $\sim 3\%$ of the original bodies survive on high–inclined orbits in the inner solar system, while less than 1% survive in the main asteroid belt; thus the highly–inclined leftovers could constitute, at the end of planetary formation, a population that is 1–10 times more numerous than the current main belt population.

The goal of this paper is to study in detail whether the population of highly–inclined leftovers could be a plausible cause of the LHB. In section 2 we describe our numerical experiments: the choice of the initial conditions for test particles and planets, the computation of the time evolution of the cratering rate on the terrestrial planets and of the impact velocities. In section 3 we compare our results with the cratering record on the Moon and compute the total number of bodies of various sizes that would be required in the highly–inclined population in order to account for the number of impacts occurred during the LHB. Section 4 discusses the advantages of this new scenario as well as the major open questions.

2. Simulation of the Late Heavy Bombardment

In the framework of their *reference simulation* of formation of the terrestrial planets, Petit et al. (2000) integrated the evolution of 100 test particles initially placed between 1 and 2 A.U. The particles rapidly acquired a large orbital inclination (Fig. 1), while their total number decayed because of collisions with the Sun and with the planetary embryos. After 100 My, the end of the accretion process of the planets, 3% of the test particles survived; all had $i > 39$ degrees and $a < 2$ A.U. To check the variability of the results on the assumed initial mass distribution of the embryos, Petit et al. also integrated test particles initially placed between 1.5 and 2 A.U. in the framework of models that assume the existence of embryos only outside 1.5 A.U., with small initial mass (twice that of the Moon). These models fail to generate Earth–mass planets in the terrestrial-planet region and thus should be considered as lower limits for the amount of dynamical excitation that occured in the inner solar system. Nevertheless, the evolution of the test particles in these *check simulations* was qualitatively similar to that of the *reference simulation*, with most of the survivors left on orbits with more moderate, but still large, inclinations (the median value being 27 degrees). This shows that the existence of highly–inclined leftover bodies is a robust consequence of planet formation.

To study the subsequent evolution of these bodies and to investigate their possible relationship with the Late Heavy Bombardment, we need to start from a larger statistical sample. For this purpose, we "cloned" the surviving particles of the *reference* simulation and of the *check* simulations with 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 Petit et al. integrations. 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. Fig. 2 shows the projections on the (a, e) and (a, i) planes of the initial location of the 200 test particles generated to mimic the orbital distribution of the leftovers of the *reference* simulation (left panels) and of the *check* simulations (right panels). In the following, we will refer to the first distribution as MODEL 1 (our reference case) and to the second one as MODEL 2 (an extreme case to check the robustness of our results).

The dynamical evolution of the particles was 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 (dots) 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 mimic the orbital distribution of the particles that survived for 100 My in Petit et al. integrations. 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 process of the Petit et al. simulations become short–lived in the framework of the present planetary configuration.

The typical endstates 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 difficultly transported to large semimajor axis by encounters with the terrestrial planets, and therefore have little chance to reach Jupiter 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 provides 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 with 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 $V(t) = \sum_n p(t, n)v(t, n)/(N \odot P(t))$. 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. 1999, 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 ($\sim$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 not lower than 30km/s. The cumulative distributions of the impact velocities on Mercury, Venus and Mars are also shown, for comparison.

3. Comparison with cratering data

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

According to Neukum and Ivanov (1994), the cratering record on the Moon indicates that the flux of projectiles during the LHB 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 collisional probability 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 cratering record, within the uncertainties of the latter.

Beyond matching the gross timescales, 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 cratering 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. 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 use the code by Melosh (1989). As a lower limit, we assume that the bodies have a density ~ 2.5 g/cm^3, because in the Petit et al. simulations most of the 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 a scaling law $D = 1.17 D_{TR}$ between the diameter D of

the observed crater and the diameter D_{TR} of the transient crater, as given by McKinnon (1997). 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 $\sim 10^7$ 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 is consistent with the result by Petit et al. that the highly–inclined leftovers could constitute a population which is 1-10 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). The important point is that, thanks to the large velocities of the highly–inclined bodies relative to the Moon ($\sim$ 30 km/sec), the size required to form a basin is not very large: according to Melosh's code, an impactor diameter of 20 km is enough for a projectile with a density of 2.5 g/cm^3. 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. 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 cratering record on the Moon. The cratering 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-Schmitt (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. However, it is also 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 simulations. 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.

4. 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., 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 cratering 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 simulations by Petit et al. (2000).
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 (partialy 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 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 underabundance 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 an overdensity of basins 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 subproduct 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 the planetary embryos in the reference simulation of Petit et al. (2000). Small bodies are denoted by asterisks or crosses, depending on their initial semimajor axis. The embryos are denoted by open circles, whose size is linearly proportional to their mass. A full–mass Jupiter exists 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 inclinaitons. 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 A.U.; the smaller has Mars' semimajor axis, but a large inclination, and a mass equal to half an Earth mass.

Fig. 2 The initial conditions of the test particles that mimic the orbital distributions of the leftover planetesimal population found in the simulations of Petit et al. (2000). The left panels refer to the Petit et al. *reference simulation* (MODEL 1), while the right panels refer to the 'check' simulations, carried out within a pessimistic model of the primordial distribution of protoplanetary embryos (MODEL 2).

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). Bottom panel: the Moon's differential distribution of impact velocities (relative frequency of impacts with velocity between v and $v + 1$km). Data are taken from the integrations of MODEL 1.

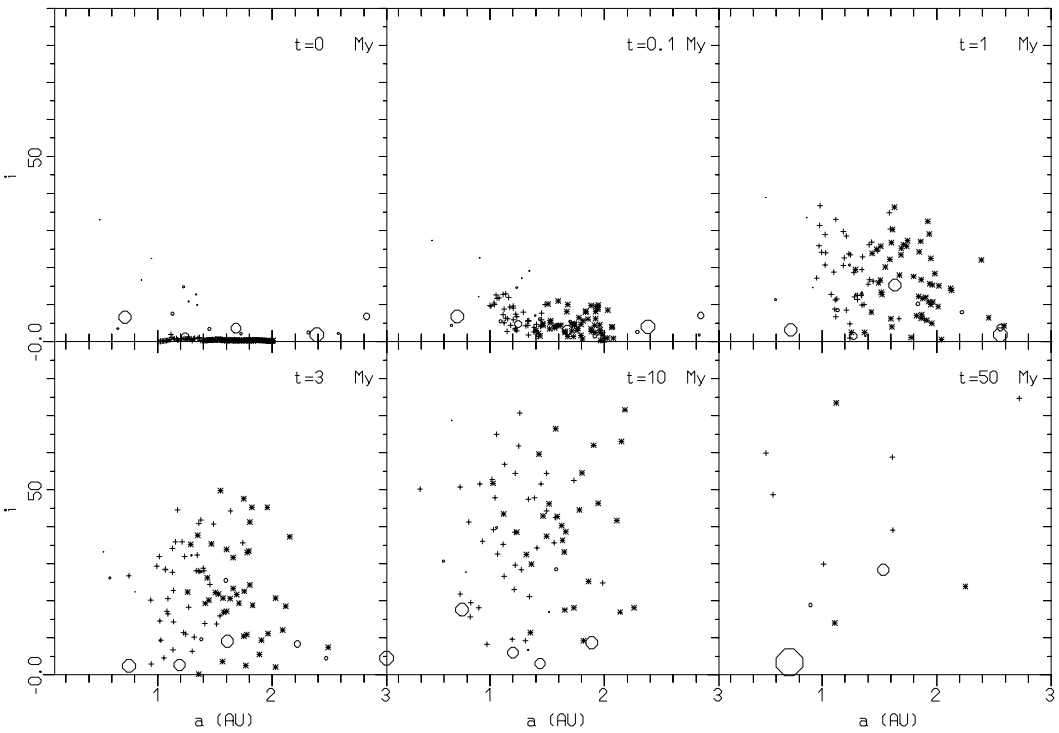

Fig. 1.

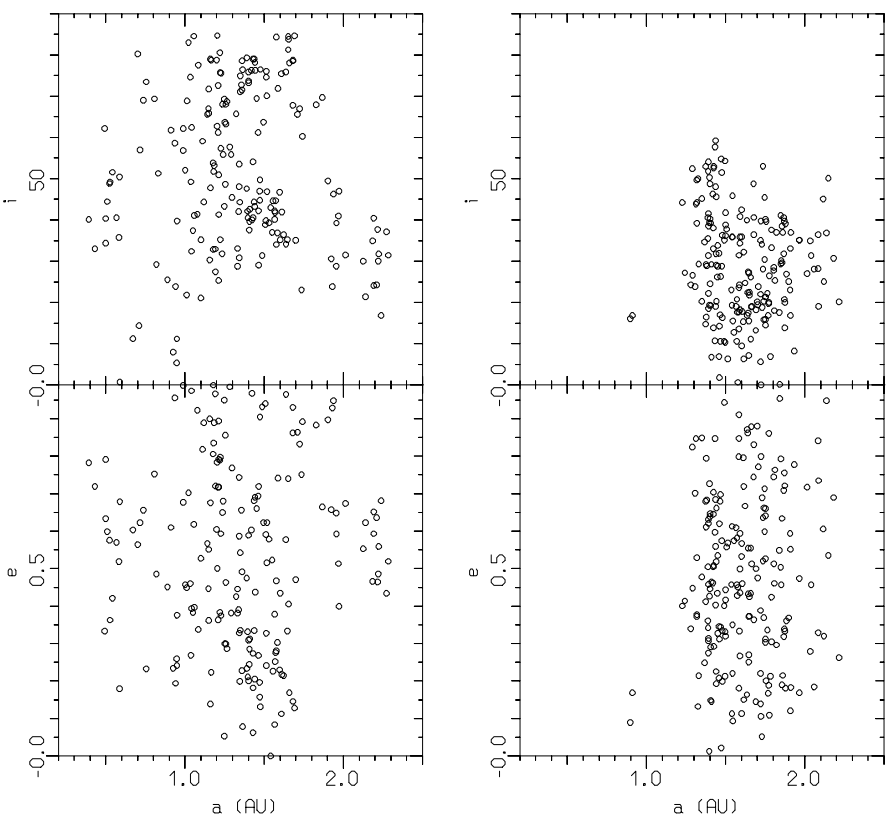

Fig. 2.

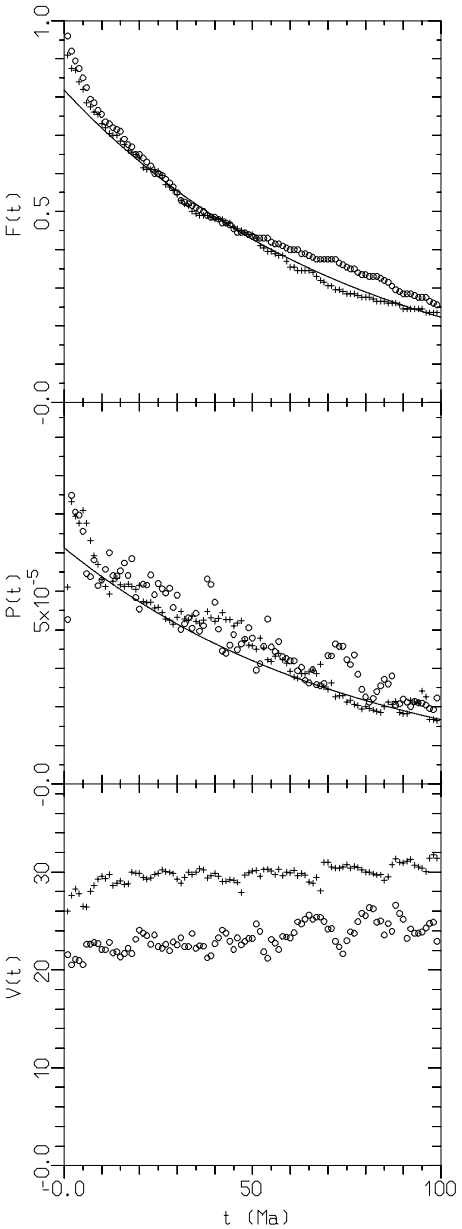

Fig. 3.

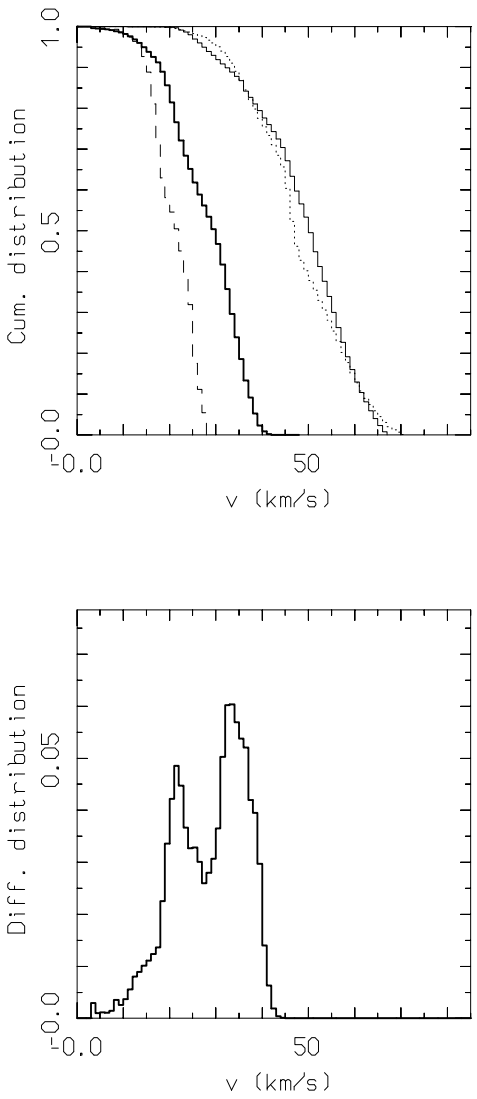
Cum. distribution
1.0
0.5
0.0
0.0
50
v (km/s)
Diff. distribution
0.05
0.0
0.0
50
v (km/s)

Fig. 4.