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# Review of the population of impactors and the impact cratering rate in the inner solar system

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**Abstract–**All terrestrial planets, the Moon, and small bodies of the inner solar system are subjected to impacts on their surface. The best witness of these events is the lunar surface, which kept the memory of the impacts that it underwent during the last 3.8 Gyr. In this paper, we review the recent studies at the origin of a reliable model of the impactor population in the inner solar system, namely the near-Earth object (NEO) population. Then we briefly expose the scaling laws used to relate a crater diameter to body size. The model of the NEO population and its impact frequency on terrestrial planets is consistent with the crater distribution on the lunar surface when appropriate scaling laws are used. Concerning the early phases of our solar system's history, a scenario has recently been proposed that explains the origin of the Late Heavy Bombardment (LHB) and some other properties of our solar system. In this scenario, the four giant planets had initially circular orbits, were much closer to each other, and were surrounded by a massive disk of planetesimals. Dynamical interactions with this disk destabilized the planetary system after 500–600 Myr. Consequently, a large portion of the planetesimal disk, as well as 95% of the Main Belt asteroids, were sent into the inner solar system, causing the LHB while the planets reached their current orbits. Our knowledge of solar system evolution has thus improved in the last decade despite our still-poor understanding of the complex cratering process.

## INTRODUCTION

Investigating the surface histories of the solid planets and satellites is a major objective of planetary exploration. Most solid bodies in the solar system display a record of accumulated impact cratering on their surfaces. These craters range in size from a few meters or smaller to hundreds of thousands of kilometers in diameter (e.g., giant basins on the Moon, Mars, and Mercury). Assuming a constant impact rate with time, the age of a surface is proportional to the number of impacts it experienced. Thus, if it is possible to estimate the rate of crater production on a surface, then the total number of craters can allow an estimate of the age of this surface. However, the cratering rate on a planet is related to the population of projectiles, and particularly their orbital and size distribution. Determining cratering rates therefore needs a good knowledge of the population of potential impactors, which allows the determination of their impact frequencies on planets. Then, a good understanding of the cratering process itself is required to establish the relationship between the diameters of the crater and the projectile as a function of the projectile's mass, velocity, impact angle, and planetary characteristics.

The only absolute chronology of craters up to 3.8 Gyr that has been studied in detail so far is the lunar chronology, which was calibrated by dating lunar samples brought back by the Apollo missions. The lunar crater-production function is the best investigated among terrestrial planet surfaces, as it is based on a large database of images at all resolutions. Conversely, we do not yet have any samples of the Martian surface; this is the main reason why there are different models to describe the Martian cratering rate. On Earth, the situation is even worse as the activity is high, and several mechanisms (e.g., erosion, plate tectonics) erase crater features over time so that the cratering record is incomplete. Of the terrestrial planets, only the Moon, Mercury, and Mars have heavily cratered surfaces, and all these surfaces have complex crater size distributions. For instance, the crater distributions of Mercury and Mars at diameters of less than 40 km are steeper than the lunar distribution due to the obliteration of a fraction of small craters by plains formation (Strom et al. 2005). On Venus, the crater density is an order of magnitude less than on Mars; only young craters are present due to resurfacing events, which erased older craters. Moreover, small craters on this planet are rare because the small impactors cannot penetrate the thick atmosphere. Finally, the crater counting can be affected by the potential presence of secondary and multiple craters.

Let us assume that all craters have been identified and counted on a surface. To determine the age of this surface, we need the relationship of a crater's diameter to an impactor's size. Scaling laws have been established for this purpose by extrapolating the results from small-scale impacts in the laboratory to large planetary impacts (see, e.g., Holsapple 1993). However, they rely on our poor understanding of the complex cratering process. Thus, major uncertainty in the estimate of both the cratering rate and the impactor population is the reliability of these scaling laws. The cratering process is still not clearly understood and relies on many unknown parameters, such as the surface conditions and the physical properties of the impactors. The physics of cratering is a major area of research that needs long-term investigation through confronting experiments, observations, and numerical models. Consequently, different values of the crater diameter are estimated as a function of the impact characteristics (mass and velocity of the projectile), or vice-versa, depending on the physical model assumed to represent this process (see Holsapple et al. 2002 for a discussion). Also, the size distribution of projectiles derived from the distribution of crater diameters and vice-versa still contain large error bars.

An alternate way of determining cratering rates is to develop a realistic model of the total population of potential planetary impactors and their impact frequencies as a function of impact energy. When convolved with the usual crater formation scaling laws, such a model can provide the resulting crater size distribution on the Moon, which can then be confronted to the actual cratering record. Once validated by this confrontation, the model can provide cratering rates on other planets.

Here we present the most recent model of the near-Earth object (NEO) population, the impact rate on the different planets, and a comparison with the actual record. We also summarize a recent scenario that has been proposed as an explanation of the Late Heavy Bombardment (LHB) and some other properties of our solar system.

## THE POPULATION OF IMPACTORS IN THE INNER SOLAR SYSTEM

Strong biases exist against the discovery of objects in some types of orbits due to the limited portion of observable space from the ground. In particular, most observations are made toward the opposition and close to the ecliptic. Consequently, the observed orbital distribution of NEOs, which constitutes the main population of impactors in the inner solar system, is not representative of the real distribution. Characterizing the impact cratering rate on planets that is caused by this population can only be achieved with complete knowledge of both the orbital and size distributions of its members.

Two methods have been developed to obtain an estimate of the real NEO population from the observed population. The first method relies entirely on data from observational surveys and tries to apply a correction for observational biases. This approach has been used on the largest detection sample size obtained by the LINEAR project (Stuart 2001). However, this direct de-biasing method requires using 1-D projections of absolute magnitude, semi-major axis $a$, eccentricity $e$, and inclination $i$ in order to beat down the small number statistics problem. Consequently, it cannot capture any potential dependency of the distribution of an orbital element on another. For instance, if a difference exists between the inclination distribution at low semi-major axes and that at large semi-major axes, this method cannot capture it, which is a severe limitation. The other method uses theoretical orbital dynamical constraints in combination with detections from observational programs with known biases. This method and its results are summarized in the following paragraphs.

From the results of the numerical integrations, it is actually possible to estimate the steady state orbital distribution of the NEOs coming from each of the main source regions of these bodies, which have been clearly identified in the last decade (see Morbidelli et al. 2002a for a complete review on this topic). In this approach, the key assumption is that the NEO population is currently in steady state. This assumption is supported by the lunar and terrestrial crater records, which suggest that the impact flux has been relatively constant (within a factor of 2) during the last 3.6 Gyr (Shoemaker 1998). To compute the steady-state orbital distribution of the NEOs coming from a given source, first the dynamical evolutions of a statistically significant number of particles, initially placed in the considered NEO source region(s), are numerically integrated. The particles that enter the NEO region are followed through a network of cells in the $(a,e,i)$-space during their entire dynamical lifetime. The mean time spent in each cell (hereafter called "residence time") is computed. The resulting residence-time distribution shows where the bodies from the source statistically spend their time in the NEO region. As it is well known in statistical mechanics, in a steady state scenario, the residence time distribution is equivalent to the relative orbital distribution of the NEOs that originated from the source. In other word, we can expect a larger number of NEOs in regions where the residence time of particles is greater.

This dynamical approach has been used with modern numerical integrations (Bottke et al. 2000, 2002). It allowed the computation of the steady-state orbital distributions of the NEOs coming from three sources: the $\nu_6$ secular resonance, the 3:1 mean motion resonance with Jupiter, and the Mars-crosser population.

The 3:1 mean-motion resonance with Jupiter occurs at approximately 2.5 AU from the Sun (see Fig. 1); its effect is to increase the orbital eccentricity of Main Belt asteroids

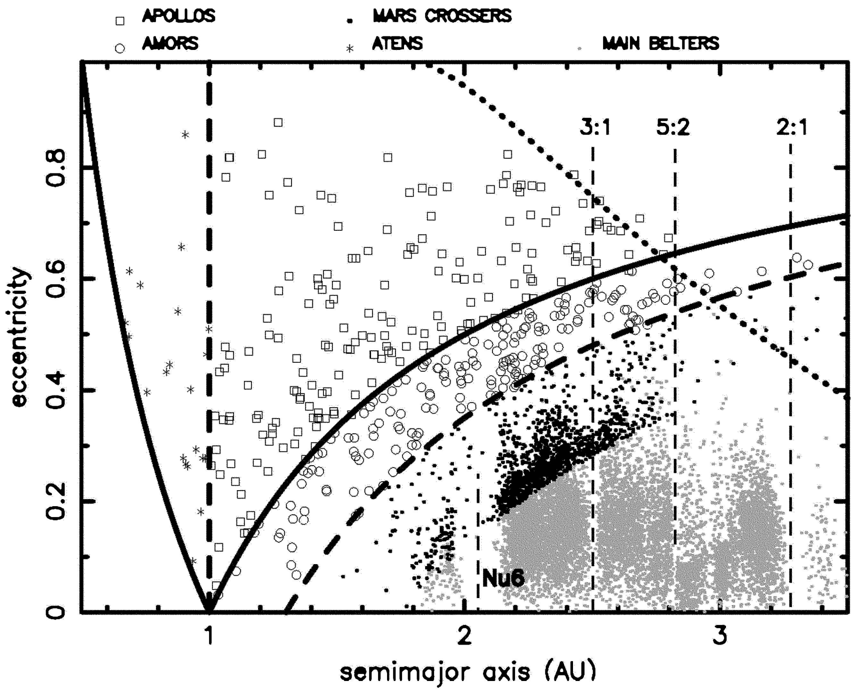


Fig. 1. Source regions of the NEO population represented in the (semi-major axis *a*, eccentricity *e*) plane. The three NEO groups, namely Atens, Apollos, and Amors, and the Mars-crossers (see Michel et al. 2000) are also indicated, as well as the location of main mean-motion resonances with Jupiter (indicated as 3:1, 5:2, 2:1) and the secular resonance Nu6 (see text for details) The full lines represent the Earth-crossing lines (perihelion and aphelion equal to 1 AU), the curved dash line represents the Mars-crossing line at perihelion, and the dotted line at the top right of the plot is the Jupiter-crossing line at the aphelion.

injected into it. When the eccentricity increases, the perihelion distance decreases, and eventually becomes smaller than the orbital radius of the Earth, so that the particle, originally Main Belt, becomes Earth-crossing. For a population initially uniformly distributed inside the resonance, the median time required to cross the orbit of the Earth is about 1 Myr, the median lifetime is about 2 Myr, and the typical end-states are a collision with the Sun (70%) and an ejection in hyperbolic orbit (28%) (Gladman et al. 1997). The mean time spent in the NEO region is 2.2 Myr (Bottke et al. 2002), and the mean collision probability with the Earth, integrated over its lifetime in the Earth-crossing region, is 0.002 (Morbidelli and Gladman 1998). The $\nu_6$ secular resonance occurs when the precession frequency of the asteroid's longitude of perihelion is equal to the sixth secular frequency of the planetary system. The latter can be identified with the mean precession frequency of Saturn's longitude of perihelion, but it is also relevant to the secular oscillation of the eccentricity of Jupiter (see chapter 7 in Morbidelli 2001). This secular resonance essentially marks the inner edge of the Main Belt; its effect depends on the location of the small body in this zone. In the region where the resonance is powerful, it causes a regular but large increase of the eccentricity of the asteroids. Earth- (or Venus-) crossing orbits can thus be reached, and in several cases the small bodies collide with the Sun as their perihelion distance becomes smaller than the solar radius. The median time required to become an Earth-crossing object, starting from a quasi-circular orbit, is about 0.5 Myr. Accounting also for the subsequent evolution in the NEO region, the median lifetime of bodies initially placed in the $\nu_6$ resonance is about 2 Myr, the typical end-states being a collision with the Sun (80% of the cases) and an ejection in hyperbolic orbit (12%) (Gladman et al. 1997). The mean time spent in the NEO region is 6.5 Myr (Bottke et al. 2002); the mean collision probability with the Earth, integrated over the lifetime in the Earth-crossing region, is about 0.01 (Morbidelli and Gladman 1998). In addition to these powerful resonances, the Main Belt is densely crossed by hundreds of thin resonances: high-order mean-motion resonances with Jupiter (where the orbital frequencies are in a ratio of large integer numbers), three-body resonances with Jupiter and Saturn (where an integer combination of the orbital frequencies of the asteroid, Jupiter and Saturn is equal to zero [Murray et al. 1998; Nesvorny and Morbidelli 1998, 1999]), and mean-motion resonances with Mars (Morbidelli and Nesvorny 1999). Many if not most Main Belt asteroids have a chaotic evolution due to this dense presence of resonances. The magnitude of this chaotic effect remains very weak so that the time required to reach a planet-crossing orbit (Mars-crossing in the inner belt, Jupiter-crossing in the outer belt) ranges from several tens of Myr to some Gyr, depending on the resonance and on the starting eccentricity (Murray and Holman 1997). The high rate of diffusion of asteroids from the inner belt can explain the existence of the population of numerous Mars-crossers. The population of Mars-crossers extends up to semi-major axes about 2.8 AU, suggesting that the phenomenon of chaotic diffusion from the Main Belt extends at least up to this threshold. To reach Earth-crossing orbits, the Mars-crossers randomly walk in semi-major axis under the effect of Martian encounters until they enter a resonance that is strong enough to further decrease their perihelion distance below 1.3 AU. For the main group of Mars-crossers (see Michel et al. 2000 for the complete characteristics of the Mars-crosser population), which is called intermediate Mars-crossers (IMC), being just an intermediate population between the Main Belt and NEOs, the median time required to become Earth-crosser is about 60 Myr; about 2 bodies larger than 5 km become NEOs every million years, which is consistent with the supply rate from the Main Belt estimated by Morbidelli and Nesvorny (1999). The mean time spent in the NEO region is 3.75 Myr (Bottke et al. 2002). Figure 1 shows the positions of the different sources in the (semi-major axis, eccentricity) plane.

The overall NEO orbital distribution has then been constructed as a linear combination of the distributions from these three different sources. The NEO magnitude distribution, assumed to be source-independent, was constructed so its shape could be manipulated using an additional parameter. The resulting NEO orbital-magnitude distribution was then observed virtually by applying the observational biases associated with the Spacewatch survey on it (Jedicke 1996). This allowed us to determine a good combination of the three distributions, which resulted in a model distribution appropriately fitting the orbits and magnitudes of the NEOs discovered or accidentally re-discovered by Spacewatch. To have a better match with the observed population at large semi-major axes, the model has been extended by also considering the steady-state orbital distributions of the NEOs coming from the outer asteroid belt ($a > 2.8$ AU) and from the Jupiter-family comets (Bottke et al. 2002). The resulting best-fit model nicely matches the distribution of the NEOs observed by Spacewatch without restriction on the semi-major axis (see Fig. 10 in Bottke et al. 2002).

An important aspect of this model is that once the values of its parameters are determined by best-fitting observations of a defined survey, the steady-state orbital-magnitude distribution of the *entire* NEO population is determined. Thus, this distribution is also valid in those regions of orbital space not sampled by any survey because of extreme observational biases. This underlines the power of the dynamical approach for debiasing the NEO population.

From this model, the total NEO population is estimated to contain about 1200 objects with absolute magnitude $H < 18$ and semi-major axis $a < 7.4$ AU. In January 2007, approximately 75% of these objects with $H < 18$ have been observed, as indicated by the number of discoveries provided by the Horizons system at the Jet Propulsion Laboratory. The NEO absolute magnitude distribution is of the type $N(<H) = C \times 10^{0.35\pm0.02H}$ in the range of $13 < H < 22$, implying 29,400 ± 3600 NEOs with $H < 22$. Assuming that the albedo distribution is not dependent on H, this magnitude distribution implies a power law cumulative size distribution with exponent $-1.75 \pm 0.1$. This distribution is in perfect agreement with that obtained in Rabinowitz et al. (2000), who directly debiased the magnitude distribution observed by the NEAT survey. We will see later that it is also consistent with the crater size distribution on the Moon ($-2$ exponent) when scaling laws are applied to derive the corresponding projectiles' size distribution.

The comparison between the debiased orbital-magnitude distribution of the NEOs with $H < 18$ and the observed distributions of discovered objects suggests that most of the undiscovered NEOs have H larger than 16, and semi-major axis in the range 1.5–2.5 AU. With this orbital distribution, and assuming random values for the argument of perihelion and the longitude of node, about 21% of the NEOs turn out to have a minimal orbital intersection distance (MOID) with the Earth smaller than 0.05 AU. The MOID is defined as the minimal distance between the osculating orbits of two objects. By definition, NEOs with MOID < 0.05 AU are classified as potentially hazardous objects (PHOs); the accurate orbital determination of these bodies is considered a top priority.

## IMPACT FREQUENCY OF NEOs WITH THE EARTH

When a small body collides with the Earth, the corresponding impact energy depends not only on the impact velocity, but also on the bulk density and size of the object. Therefore, to estimate the probability of collision with the Earth as a function of the impact energy, the absolute magnitude distribution of NEOs must be converted into a size distribution of this population. Because H is related to the diameter by the albedo, it is first necessary to estimate the albedo distribution. The albedo is also used to estimate the body's bulk density.

Two independent approaches have been used to estimate the NEO albedo distribution (Morbidelli et al. 2002b; Stuart and Binzel 2004). The results obtained by these two methods are in very good agreement. In particular, both imply that on average, the usually assumed conversion $H = 18 \Leftrightarrow D = 1$ km slightly overestimates the number of kilometer-size objects. There should be ~1000 NEOs with $D > 1$ km, against ~1200 NEOs with $H < 18$. Once the albedo distribution is determined, a similar procedure is used by Morbidelli et al. (2002b) and Stuart and Binzel (2004) to estimate the NEO collision probability with the Earth as a function of collision energy. It is assumed that the density of bright and dark bodies is 2.7 and 1.3 g/cm$^3$, respectively. These values are taken from spacecraft or radar measurements of a few S-type and C-type asteroids. The collision probability is then computed using the model described by Bottke et al. (1994). This

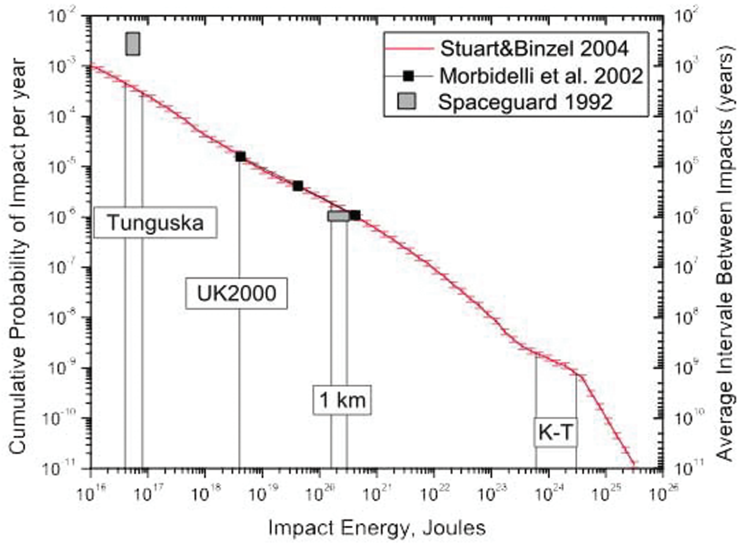


Fig. 2. Collision probability as a function of impact energy from Stuart and Binzel (2004). The error bars represent uncertainty in the number of NEOs but do not account for the uncertainty in their densities. Vertical lines represent the energy (or range of energies) for various events: the Tunguska event that occurred in 1908 (Sekanina 1998), the energy assumed by the UK NEO Task Force as a threshold for large-scale regional destruction (UK NEO Task Force 2000), the energy of impact of a 1 km object (with impact velocity of 20.9 km/s and a bulk density of 1400 kg/m$^3$ or 2700 kg/m$^3$), and the energy of the K-T impact event that formed the Chixculub crater (Pope et al. 1997). Courtesy of J. S. Stuart.

model, which is an updated version of previous ones, is based on the assumption that the values of the mean anomalies of the Earth and the NEOs are random. The gravitational attraction exerted by the Earth is also included. There is a remarkable agreement between the final results of Morbidelli et al. (2002b) and Stuart and Binzel (2004), as shown in (Fig. 2). In particular, it is found that the Earth should undergo a 1000 megaton collision every 50,400 ± 6400 years. Such impact energy is on average produced by bodies with $H <$ 20.5. The NEOs with $H < 20.5$ discovered so far represent only about 28% of the total population and carry about the same percentage of this collision probability.

## COMPARISON WITH THE ACTUAL CRATERING RECORD ON TERRESTRIAL PLANETS

In the inner solar system, only the Moon, Mercury, and Mars have heavily cratered surfaces, and the crater size distribution is very complex in all cases. In particular, for craters with diameters smaller than 40 km, the size distributions for Mercury and Mars are shallower than those of the lunar highlands. This is interpreted as being due to the plains formation on those planets, which has obliterated a fraction of the small craters (Strom et al. 2005). Therefore, the lunar crater-production function is still the best investigated and the most reliable function among terrestrial planet surfaces, as it is based on a large database of images at all resolutions. Note that the Mars Global Surveyor Mars Orbiter Camera (MOC) has recently acquired data that can help establish the present-day impact cratering rate on Mars's surface, based on the observation of 20 impact craters with diameters in the range 2–150 m created in an area $21.5 \times 10^6$ km$^2$ between May 1999 and March 2006 (Malin et al. 2006). The authors conclude that the values predicted by models that scale the lunar cratering rate to Mars are close to the observed rate. This result supports the usefulness of the Moon, which has the most reliable and complete cratering record, in understanding the projectile flux on terrestrial planet surfaces.

Complicating matter is the fact that the comparison between the rate of craters produced by a projectile population (such as our model of the NEO population) and the observed craters on the Moon requires using appropriate scaling laws. A number of studies on the physics of impact cratering of solid bodies have derived projectile-crater scaling laws. The interested reader may consult Melosh (1989) for a discussion of some of the approaches leading to scaling laws, as well as discussions concerning the mechanics of shock processes and cratering. What we mean exactly by the scaling of impact events is to apply some relation, the scaling law, to predict the outcome of one event from the results of another, or to predict how the outcome depends on the problem parameters. The parameters that are different between the two events are the variables that are "scaled." Most often those are the size scale or the velocity scale, but they can also include other parameters, including a gravitational field or a material strength (see, e.g., Holsapple 1993). A number of questions can be raised about such scaling laws. Clearly they are the outcome of complex processes involving the balance equations of mass, momentum, and energy of continuum mechanics and the constitutive equations of the materials. The impact processes encompass the gamut of pressures from many megabars where common metals act like a fluid, to near zero where material strength or other retarding actions limit the final crater growth. Thus, the estimated mass of an impactor varies significantly depending on which crater scaling law is chosen. Converting craters from their present diameter to a transient diameter (properly accounting for crater collapse) and then to a projectile size involves a number of assumptions. One could therefore ask whether scaling laws should be some kind of power-laws or whether simple algebraic results can be expected for such complex phenomena. Possible approaches to determining such scaling laws include experiments, analytical solutions to the governing equations, or code calculations using those same equations. Each approach has its uses but also its deficiencies (see Holsapple 1993 for a summary).

Stuart and Binzel (2004) used three crater scaling laws to compare the rate of crater formation expected from the NEO population that they derived, which is consistent with the model of NEO population of Bottke et al. (2002), with the observed craters on the Moon. They indicated these three scaling laws as being Melosh's Pi-scaling (Melosh 1989), Shoemaker's formula (Shoemaker et al. 1990), and Pierazzo's formula (Pierazzo et al. 1997). In fact, as stated in Melosh (1989), the Pi-group scaling has been defined by Holsapple and Schmidt (1982) on the basis of small-scale laboratory experiments in a centrifuge; Pierazzo's formula is just a different analytical form of these laws. In contrast to the Pi-scaling, Shoemaker's formula has been derived from explosion-cratering experiments. Such experiments allow the investigation of events on a larger scale in comparison to centrifuge experiments. Nevertheless, all explosion events are still small in comparison with natural impact craters. Then, experiments based on impacts are performed with velocities lower than ~7 km/s. Hence, impact cratering on terrestrial planets involving impact velocities of several tens of km/s can only be estimated by extrapolation of the experimental data to higher velocities (for all craters) and to large crater sizes (for large impact craters). Numerical models can help partially refine scaling laws, but these models are also limited by the physics that we put into them, which is poorly known, and by their numerical resolution.

Despite these large uncertainties in scaling laws, Stuart and Binzel (2004) find that when corrections are accounted for, the following formulae adapted from Shoemaker et al. (1990) produce the best match between the NEO population and the observed craters:

$$\begin{aligned}
D_t &= 0.01436\left(W\frac{\rho_i}{\rho_t}\right)^{1/3.4}\left(\frac{g_e}{g_t}\right)^{1/6}(\sin\alpha)^{2/3} \\
D_r &= 1.56D_t \\
D_f &= D_r \quad \text{if } D_r \le D_* \\
D_f &= \frac{D_r^{1.18}}{D_*^{0.18}} \quad \text{if } D_r > D_* \\
D_* &= 4\text{km}\left(\frac{g_e}{g_t}\right)
\end{aligned} \qquad (1)$$

where all units are mks, $D_t$, $D_r$, and $D_f$ refer to transient, rim-to-rim, and final crater diameters, respectively, $\rho$ and $g$ are density and gravity with subscripts $i$, $t$, and $e$ indicating impactor, target, and Earth, respectively, while $\alpha$ ($=\pi/2$ for vertical impacts) is the impact angle. These scaling laws allow us to convert the impact rates given in the previous section as a function of impactor size into rates of crater production for craters larger than a given size on different planets. Note that the estimated rate with this method corresponds to the current rate of crater production from NEOs. However, keeping the assumption that the model of the NEO population represents the steady-state population, the computed rate represents the steady-state cratering rate, which can be compared with the historical cratering record. The only severe mismatch is found when the results are compared to the highlands crater production function below 10 km, as the highlands crater production function is a factor 3 or more lower than the function based on the NEO population model (Stuart and Binzel 2004). The reason of this discrepancy is not clear, as the NEO model, the crater counting, and the scaling laws all contain uncertainties. However, Strom et al. (2005) indicate that this function is consistent with the size distribution of the Main Belt population, which is shallower than that of NEOs. If the Main Belt population is directly responsible for the highlands crater production function, this implies that at the time of the formation of the craters on the highlands (the so-called LHB), the asteroids were escaping from the Main Belt via a size-independent process. This excludes non-gravitational effects, such as the Yarkovsky effect (which is responsible for the current production of NEOs; hence the different size distributions between NEOs and Main Belt asteroids). The only gravitational process that can eject asteroids from all over the asteroid belt is the sweeping of resonances, which is caused by the orbital migration of the giant planets. This is consistent with the recently proposed scenario that reproduces the LHB and other characteristics of our solar system (see the Early Cratering History of the Solar System section).

Bland and Artemieva (2006) have recently studied the rate of small impacts on Earth by taking into account the interaction between bolides and the Earth's atmosphere, coupled with a knowledge of the impact rate at the upper atmosphere, in order to help complete the small terrestrial crater record. They constructed a complete size-frequency distribution for terrestrial impactors, both on the Earth's surface and in the upper atmosphere. Their analysis of the effect of the passage through Earth's atmosphere suggests that fragmentation is the rule for all impactors smaller than 1 km. Therefore, single craters smaller than 10–20 km across may well have been produced by the simultaneous impact of closely spaced fragments rather than a single impactor. The analysis of the upper atmosphere data set suggests that Tunguska events should happen approximately every 500 years. Taking the curve for the upper atmosphere and scaling it to the Earth's surface based on their modeling results, they find that craters 100 m in diameter are formed on the Earth's land area every 500 years, 0.5 km

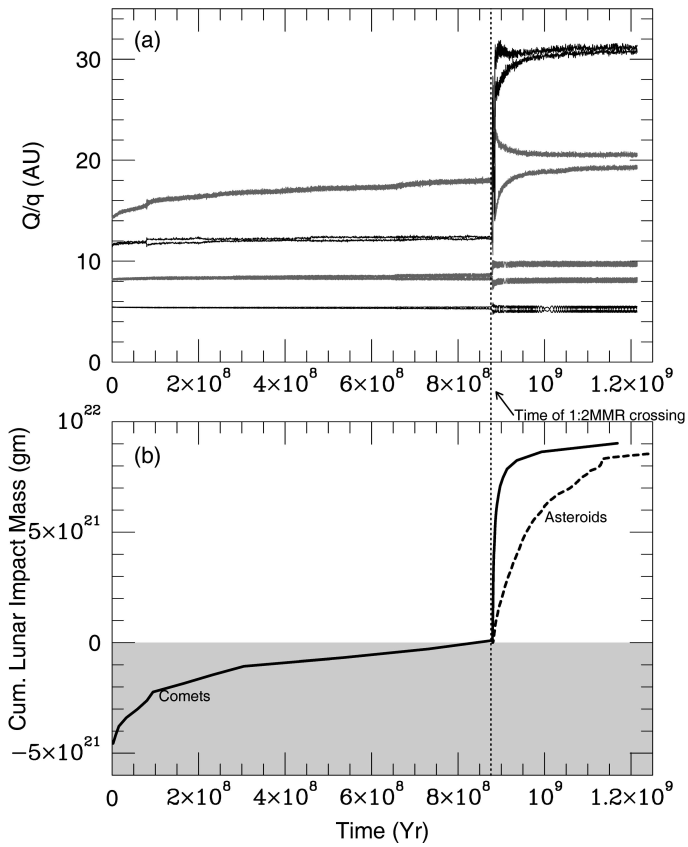


Fig. 3. a) Evolutions of the perihelion and aphelion distances of Jupiter, Saturn, Uranus, and Neptune until they reach their current orbits (from Gomes et al. 2005). The label 1:2 MMR means that Jupiter and Saturn are in their mutual 1:2 mean motion resonance. When this happens (at 880 Myr in this case), the planetary system is suddenly destabilized. In particular, Uranus and Neptune reach their current orbit. On this plot, note that Neptune is initially at a smaller distance to the Sun than Uranus, but other simulations reproduce the current orbits starting with a more distant Neptune than Uranus. b) Cumulative mass of comets (full curve) and asteroids (dashed curve) at 1 AU from the Sun (Earth's distance). The comet curve is offset so that its value is zero at the time of 1:2 MMR crossing. At this time, there is a drastic increase of material's mass reaching 1 AU over a 100–200 Myr period, which is in agreement with the magnitude and duration of the LHB from the lunar crater record. Note that in addition to comets, 95% of the asteroids escape from the Main Belt and contribute to (or even dominate) the impactor population (see Gomes et al. 2005 for details on these calculations).

craters every 21,000 years, and 1 km craters every 52,000 years. The authors claim that these rates are consistent with meteorite flux data from camera network and desert studies. In the $<10^5$ kg range, they are also consistent with the production of small recent craters in Australia for which both the time period and location should allow preservation of even small impact features. The surface flux curve that they derived is also consistent with, but slightly higher than, the size-frequency distribution for craters on Earth 2–10 km in diameter. They suggest that the primary cause of the departure from the expected asteroidal size-frequency distribution for craters smaller than 10 km in diameter is atmospheric disruption, even though erosion becomes also increasingly important for smaller craters.

The NEO population model and the associated collisional probability on planets allow us to also predict the formation of $2.73 \times 10^{-14}$ craters 4 km in diameter per square kilometer per year on the Moon, which compares well with the estimate obtained from crater counting on lunar terrains with a known age ($3.3 \pm 1.7 \times 10^{-14}$ /km$^2$/yr) (Grieve and Shoemaker 1994). A comparison of global impact rate of bolides has been performed by Ivanov (2006) with the steady-state cratering rate on the Moon in the past 100 Myr. From this comparison, the author suggests that the current meteoroid flux in the Earth-Moon system is approximately the same as in the last 100 Myr, provided most of the small craters (diameters smaller than 200 m) counted on the lunar surface younger than 100 Myr are primary, not secondary craters. The contamination by small secondary craters is estimated not to exceed 25–50%, so that most published results of impact crater datings on the Moon may not have to undergo severe revisions based on this argument (see, e.g., Bierhaus et al. 2005).

When accounting for the size distribution of large NEOs (e.g., N (>D) ~ $D^{-1.75}$ for D > 200 m), the model of the NEO population predicts that, relative to Earth, the production rate of craters of a given size per unit surface is 1.2 on Mars due to the increased number of impactors provided by the intermediate Mars-crosser population. These impact rates are mostly due to asteroids. Jupiter-family comets account for just 1% of the impact rate. Long-period and Halley-type comets are not explicitly accounted for in this model, but their contribution might not exceed 5% of the total crater rate on Earth (which may increase by a factor about 3 during putative comet showers).

## THE EARLY CRATERING HISTORY OF THE SOLAR SYSTEM

The estimates presented in the previous section hold only for the last 3.6 Gyr, even though some fluctuations may have occurred when, for instance, an asteroid family is formed in the Main Belt, which can lead to chronicle impact showers (Zappalà et al. 1998). In earlier periods, the impactor flux may have been different. In particular, although the interpretation of data is still subject to debate (see e.g., Hartmann et al. 2007 for an alternative view), there is a growing consensus that there has been a cataclysmic spike in the cratering rate in the inner solar system, about 700 Myr after the planets formed (see e.g., Hartmann et al. 2000; Ryder et al. 2000; Koeberl 2004, 2006). Several models have been proposed to explain this spike, which is usually called the LHB (see e.g., Levison et al. 2001; Chambers and Lissauer 2002; Levison et al. 2004). A recent study has proposed a scenario that does not only explain the LHB (Gomes et al. 2005), but also other properties of the outer solar system, such as the current orbital architecture of the giants planets (Tsiganis et al. 2005) and the existence and orbital distribution of Jovian Trojans (Morbidelli et al. 2005). Other models may be proposed to explain the LHB, but the strength of this model is that it is the only one so far that reproduces several constraints at the same time. The main assumptions are that the four giant planets initially had circular orbits, were much closer to each other ($5 < a < 15$ AU) and were surrounded by a massive disk of planetesimals of about 35 Earth masses. Dynamical interactions of the planets with this disk caused a slow increase of the orbital separations of the planets. After 500–600 Myr, Jupiter and Saturn crossed their mutual 1:2 mean motion resonance, which destabilized the planetary system as a whole: the orbital eccentricities of these two planets reached their current values, Uranus and Neptune reached their current orbit (see Fig. 3), and a huge flux of planetesimals was suddenly transported to the orbits of terrestrial planets from both the asteroid belt and the original trans-Neptunian disk. Simulations show that about $10^{22}$ g of bodies hit the Moon during a ~100–200 Myr interval (see Fig. 3), which is consistent with the magnitude and duration of the LHB from the lunar crater record. This model is indirectly supported by Strom et al. (2005). Because the crater size distribution of old terrains on the Moon is consistent with that of Main Belt asteroids, these authors concluded that the LHB was triggered by a late migration of Jupiter and Saturn, as suggested by Gomes et al. (2005).

## CONCLUSIONS

The impact cratering rates on planets give us some insights into the history of our solar system. However, determining the size distribution of individual craters is a difficult task, and relating a crater size to the size of the impactor requires a good understanding of the cratering process. Both problems will still be the subject of many studies. In recent years, the population at the origin of most of the craters on terrestrial planets, i.e., the NEO population, has been characterized in terms of its orbital and size distribution, but there are still some unknowns concerning the contribution of cometary bodies. However, our model of the NEO population and its impact frequency on terrestrial surfaces is consistent with the best characterized crater distribution, that of the lunar surface, when appropriate scaling laws are applied to convert the impactor size distribution to the distribution of crater diameters. Our knowledge has thus improved in the last decade, thanks to observational and theoretical studies, but it is clear that there are still many uncertainties about the impact process, its history in the solar system, and the identification of craters on the surfaces of terrestrial planets.

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