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A sawtooth-like timeline for the first billion years of lunar bombardment

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ABSTRACT

We revisit the early evolution of the Moon's bombardment. Our work combines modeling (based on plausible projectile sources and their dynamical decay rates) with constraints from the lunar crater record, radiometric ages of the youngest lunar basins, and the abundance of highly siderophile elements in the lunar crust and mantle. We deduce that the evolution of the impact flux did not decline exponentially over the first billion years of lunar history, but also there was no prominent and narrow impact spike $\sim$3.9 Gy ago, unlike that typically envisioned in the lunar cataclysm scenario. Instead, we show the timeline of the lunar bombardment has a sawtooth-like profile, with an uptick in the impact flux near $\sim$4.1 Gy ago. The impact flux at the beginning of this weaker cataclysm was 5–10 times higher than the immediately preceding period. The Nectaris basin should have been one of the first basins formed at the sawtooth. We predict the bombardment rate since $\sim$4.1 Gy ago declined slowly and adhered relatively close to classic crater chronology models (Neukum and Ivanov, 1994). Overall we expect that the sawtooth event accounted for about one-fourth of the total bombardment suffered by the Moon since its formation. Consequently, considering that $\sim 12-14$ basins formed during the sawtooth event, we expect that the net number of basins formed on the Moon was $\sim 45-50$. From our expected bombardment timeline, we derived a new and improved lunar chronology suitable for use on pre-Nectarian surface units. According to this chronology, a significant portion of the oldest lunar cratered terrains has an age of 4.38–4.42 Gyr. Moreover, the largest lunar basin, South Pole Aitken, is older than 4.3 Gy, and therefore was not produced during the lunar cataclysm.

1. Introduction

The temporal evolution of lunar bombardment is a subject of intense debate. A natural expectation is that it declined with time during the early epochs of solar system history, while planetesimals left over from planet accretion were in the process of being gradually removed by dynamical and collisional mechanisms.

In this respect, a surprise came with the first analysis of the lunar samples collected by the Apollo missions. They revealed a clustering of radiometric impact ages at about 3.9 Gy ago (Papanastassiou and Wasserburg, 1971a, 1971b; Wasserburg and Papanastassiou, 1971; Turner et al., 1973). Tera et al. (1974) concluded that a major bombardment episode occurred on the Moon at that time, i.e., about 0.6 Gyr after the Moon formation (4.5 Gy ago; see e.g. Kleine et al., 2009), which they named *terminal lunar cataclysm*. More recently, laboratory analyses on lunar meteorites, which should be more representative of the entire lunar surface than the Apollo samples, confirmed the strong deficit of impact ages older than $\sim$4 Gy (Cohen et al., 2000), although they did not show a narrow impact spike. This absence of older ages is consistent with the cataclysm hypothesis, but it has been argued that it could also be the result of biases that work against finding samples with the oldest impact ages (Hartmann, 1975, 2003; see Hartmann et al., 2000 and Chapman et al., 2007 for reviews of the contrasting arguments).

An analysis of lunar crater densities also fails to yield an unambiguous view of the temporal evolution of lunar bombardment. Neukum and Wilhelms (1982) (see also Neukum, 1983; Neukum and Ivanov, 1994, hereafter NI94) studied the crater density over terrains of "known" radiometric age. They concluded that the bombardment rate was roughly constant (within a factor of 2 or so) until 3.5 Gy ago, a result that is generally accepted today. In addition, they argued for a long *smooth* decay of the impactor flux at older times. Thus, in their model, there is no lunar cataclysm. The problem, however, is that only the youngest units, starting with the Imbrium basin 3.8–3.9 Gy ago, have well established radiometric ages, whereas the ages of older basins, like Nectaris, are uncertain (e.g., Norman et al., 2010). Neukum and collaborators assumed the age of Nectaris basin was $\sim$4.1 Gy because this age appears in the samples collected by the Apollo 16

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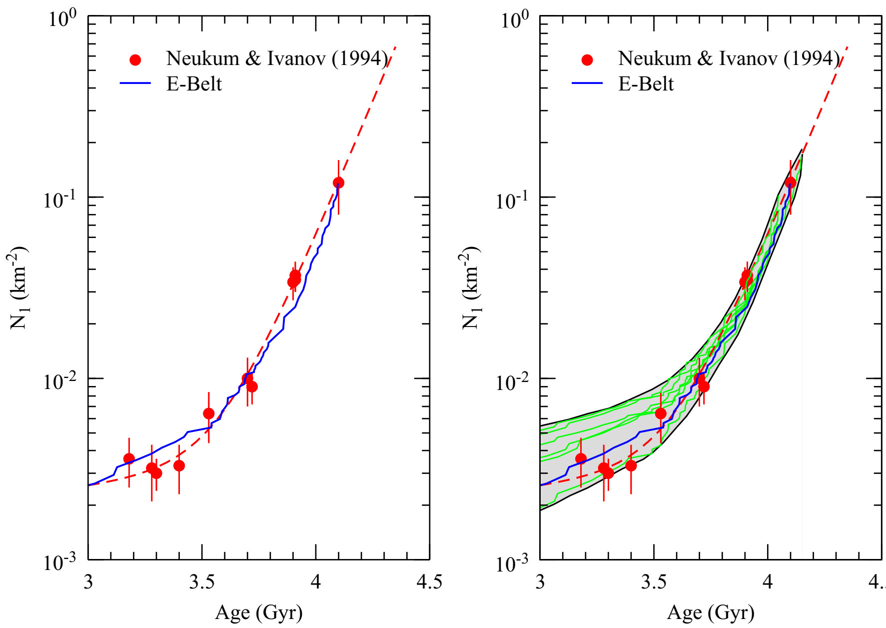

Fig. 1. In both panels, the dashed red curve shows the density of craters larger than 1 km diameter (N_1) as a function of the unit's age, according to NI94. This curve has equation $N_1 = 5.44\times10^{-14}(e^{6.93t}-1)+8.38\times10^{-4}\,t$, where t is measured in Gy. The blue curve is the same, but it follows the E-belt model (Bottke et al., 2012), assuming that the E-belt was destabilized 4.1 Gy ago. The dots with the vertical error bars show the density of craters on the terrain calibration units according to crater counts and ages reported in NI94. The Nectaris basin data-point is the first from the right. Notice that the density of $D>1$ km craters is not directly measured on the oldest units (because of saturation and degradation of small old craters and the presence of secondary younger craters); instead, it is estimated from the density of larger craters (typically with $D>20$ km, i.e., N_{20}) assuming a SFD for the crater production function. Here, for comparative purposes, for the E-belt model we have converted N_{20} into N_1 using the same crater SFD adopted in NI94. The green curves on the right panel show different E-belt models obtained by changing assumptions on the age of Orientale basin and on the total E-belt population within ranges that allow to fit the data reasonably well for $t>3.5$ Gy. We also add the contribution of MB-NEAs, assuming different bombardment rates, constant with time and up to the current value. The shaded area is the envelope of the models that we consider acceptable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mission that landed in the lunar highlands near Nectaris (e.g., Maurer et al., 1978). In this case, the density of craters as a function of age between 4.1 and 3.5 Gy ago seems to decline as $\exp(-at)$, where $a=6.93$ and t is measured in Gy (see Fig. 1). This exponential evolution was then extrapolated backwards in time by NI94, to estimate the impact flux during the oldest lunar epochs.[1]

A different view is summarized by Ryder (1990), Stöffler and Ryder (2001), and Ryder (2002). They argued that the age of Nectaris is 3.9 Gy because this age appears more prominently than the 4.1 Gy age among Apollo 16 Descartes terrain samples. If one assumes this age, then the *same* crater counts on Nectaris imply a bombardment rate that has a *much steeper* decline over the 3.5–3.9 Gy period than in NI94. This steeper decline cannot be extrapolated in time back to the lunar formation event because it would lead to unrealistic physical implications. For instance, the Moon would have accreted more than a lunar mass since its formation (Ryder, 2002)! Consequently, this scenario implies that the bombardment rate could not have declined smoothly, but rather should have been smaller before 3.9 Gy ago than in the 3.5–3.9 Gy period, in agreement with the cataclysmic impact spike hypothesis. In fact, in an end-member version, Ryder (1990) also suggested that *all* impact basins could have formed during such a cataclysm impact spike.

The most recent analysis of Apollo 16 samples suggest that the younger ages from the Descartes terrain are probably ejecta from Imbrium (Norman et al., 2010). The older ages, however, have no diagnostic link to Nectaris basin ejecta. This means the age of Nectaris remains uncertain, and may or may not be represented among Apollo 16 samples. Thus, no definitive conclusion can be derived in favor of the cataclysm or the smooth exponential decline hypothesis from these data.

Other studies on the lunar crater record reported support for a lunar cataclysm. Strom et al. (2005) detected a change in the Size Frequency Distribution (SFD) of old craters (i.e., on the highlands) relative to young craters (i.e., on the maria plains). Marchi et al. (2012) detected the signature of a change in the velocity of the projectile populations hitting the Moon at Nectarian and pre-Nectarian times, respectively. Both findings suggest drastic changes in the impactor populations of the solar system, consistent with the cataclysm hypothesis. However, an opposing viewpoint has been suggested by Fassett et al. (2012). They also found two populations of projectiles, but the transition from one to the other occurred in mid-Nectarian epoch, i.e., in the middle of the putative cataclysm. They interpreted this result as problematic for the lunar cataclysm scenario. Therefore, it is fair to say that interpreting the early cratering record of the Moon is challenging.

In this paper, we choose not to enter into those technical debates, but instead revisit the problem with a new combination of theoretical considerations (by looking at the dynamical evolution of plausible projectile sources) and existing physical constraints. More precisely, we look to calibrate the “free parameters” of the problem (i.e., size of the projectile population, timing of the instability that released the projectiles from a formerly stable reservoir, the approximate age of Nectaris basin) to produce a model that is consistent with (i) the possible dynamical evolution of the solar system, (ii) the lunar crater record and (iii) particular geochemical constraints derived from lunar samples. As we will show, our results support a view that is somewhat intermediate between the two end-member camps described above: all lunar basins forming in a smooth bombardment decline or a prominent and narrow impact spike 3.9 Gy ago. In fact, we will argue for the need of a sudden

[1] NI94 also used as a data-point the density of craters on the lunar highlands, but the age of the latter (which NI94 assumed to be 4.35 Gy) is not well constrained.

increase in the lunar impact rate, but as early as $\sim$4.1−4.2 Gy ago, and not one as pronounced as in Ryder's (1990) description of the lunar cataclysm. Consequently, we believe the lunar cataclysm implies a decline of the bombardment rate since 4.1 Gy ago, in agreement with that described by NI94. Our view was proposed before (e.g., Fig. 3 in Hartmann et al., 2000), but never quantified through a calibrated model.

2. The Nice model and the E-belt

The so-called *Nice model* (Tsiganis et al., 2005; Morbidelli et al., 2005; Gomes et al., 2005), named after Nice, France where it was developed, showed that an impact spike on the terrestrial planets is possible and plausible due to a sudden change in the orbital configuration of the giant planets. For a recent review of the model, the reader can refer to Morbidelli (2010). For the purposes of this paper, we limit our discussion to the implications of the model and how its latest developments affect the interpretation of the lunar bombardment record.

The Nice model argues that there were two distinct categories of projectiles during the impact spike: comets from the trans-Neptunian disk that likely hit inner solar system targets over a time span of several tens of millions of years, and asteroids from the region between Mars and Jupiter, most of which hit over hundreds of millions of years. Both reservoirs would have been partially destabilized as the giant planets migrated from their original to their current orbits.

The densely cratered surfaces of outer planet satellites like Iapetus hint at the possibility that destabilized comets struck the Jovian planets' satellites during ancient solar system times, in agreement with the predictions of the Nice model (Morbidelli et al., 2005; Nesvorný et al., 2007a, 2007b; Charnoz et al., 2009; Brož et al., 2011). The evidence for a cometary bombardment becomes more elusive as one moves toward the inner solar system. On the Moon, the SFD of the most ancient craters has the same shape as that of main belt asteroids (Strom et al., 2005; Marchi et al., 2009, 2012). Also, studies of platinum-group elements in ancient lunar samples, which presumably were delivered by lunar impactors, show that many projectiles were not predominantly composed of primitive, carbonaceous chondritic material. This suggests that comets did not play a major role in the ancient bombardment (Kring and Cohen, 2002; Galenas et al., 2011). The same reasoning can be applied to the analysis of the projectile fragments in regolith breccias collected at the Apollo 16 site (Joy et al., 2012). This absence of evidence for cometary impactors can be understood if physical disintegration, possibly due to explosive ice sublimation, decimated the cometary population as it penetrated into the inner solar system (e.g., Sekanina, 1984). The issue is discussed at length in Bottke et al. (2012).

Concerning asteroids, it was initially thought that objects within the current boundaries of the asteroid belt would provide a sufficient source for the lunar cataclysm (Levison et al., 2001; Gomes et al., 2005). A more detailed study of the orbital evolution of the terrestrial planets and primordial asteroid belt, however, showed there is a limit to how much mass could conceivably be extracted during giant planet migration. Brasser et al. (2009) and Morbidelli et al. (2010) argued that, among all of the possible giant planet evolutionary pathways that could take place during the Nice model, the one that actually occurred had to have been characterized by a fast displacement of Jupiter's orbit, presumably due to an encounter with another planet. They named this a *jumping-Jupiter-type evolution case*.[2]

[2] The terminology "jumping-Jupiter" was originally introduced in Marzari and Weidenschilling (2002), in the context of a study on the evolution of extra-solar planets.

Morbidelli et al. (2010) showed that this evolution only removed about 50% of the asteroids from within the current boundaries of the asteroid belt, far less than in the non-jumping-Jupiter-type evolution cases of Levison et al. (2001) and Gomes et al. (2005). An additional factor of 2 in mass would be lost by main belt objects that suddenly found themselves within mean motion or secular resonances. Note that the interested reader can find a complementary study in Minton and Malhotra (2011). Together, these works showed that destabilized main belt asteroids would only produce 2–3 basins on the Moon, not enough to match lunar cataclysm constraints (Bottke et al., 2012).

The most recent development of the Nice model is the so-called *E-belt* concept (Bottke et al., 2012). It stems from the realization that the current inner boundary of the asteroid belt ($\sim$2.1 AU) is set by the ν_6 secular resonance whose existence is specifically related to the current orbits of Jupiter and Saturn. More specifically, this resonance moves towards the Sun as the orbital distance between Jupiter and Saturn increases. Moreover, its strength depends on the eccentricities of the giant planets. Before the giant planets changed their orbital configuration, Jupiter and Saturn were closer to one another and were on more circular orbits; therefore the ν_6 resonance was not present where it is now: it was located beyond the asteroid belt and it was much weaker. Hence, the asteroid belt could extend down to the actual stability boundary set by the presence of Mars (i.e., down to 1.7–1.8 AU, depending of the original eccentricity of the planet). This putative extended belt population (E-belt) between 1.7 and 2.1 AU was almost fully depleted when the orbit of Jupiter (and the ν_6 resonance) "jumped" to their current locations. The few survivors from the E-belt would now make up the population of Hungaria asteroids (a group of high-inclined bodies at 1.8–2.0 AU).

There are two free parameters in the E-belt model that need to be set. One is the total population in the E-belt region. The second one is the time at which the E-belt was destabilized by the jump of Jupiter's orbit. Neither are constrained a priori by the dynamical models.

The total E-Belt population was calibrated by Bottke et al. (2012) in two ways. The first calibration was provided by the Hungaria asteroids. Using numerical simulations, they calculated that roughly $\sim 10^{-3}$ of the E-belt population survived in the Hungaria region until the present time. Then, using observational constraints from the current Hungaria population, they estimated the original E-belt population as 1000 times larger.

The second calibration was provided by the current main belt population. It is reasonable to expect that the E-belt region was as densely populated as the rest of the primordial main belt just before late giant planet migration took place. Estimating that 75% of the primordial main belt population was removed during resonance sweeping (via the jumping Jupiter phase), Bottke et al. used the current asteroid population to compute the original orbital density of asteroids in the main belt as a function of asteroid size and applied it to the E-belt region. The orbital volume of the E-belt is about 16–18% of the main belt orbital volume. Thus, assuming that asteroids had eccentricity and inclination distributions similar to those in the current main belt, this implies that the E-belt carried 16–18% of the primordial main belt mass, or equivalently 60–70% of the current main belt mass.

This procedure implicitly assumes that the SFD of the E-belt asteroids was the same as that of the main belt asteroids, which is reasonable because the E-belt was simply an extension of the main asteroid belt. Both SFDs are assumed to be the same as the current SFD of the main belt, which is justified because the shape of the latter has probably only experienced minor modifications by collisional evolution over the last 4 Gy (Bottke et al., 2005; Strom et al., 2005).

The two E-belt calibrations described above yield results similar to each other, which gives us increased confidence in the coherence of the E-belt model.

Determining the destabilization time of the E-belt is less straightforward. The numerical simulations in Bottke et al. (2012) yield the fraction and impact velocities of the original E-belt population that should have hit the Moon. From this information, using the E-belt population described above and applying the crater scaling relationships described in Schmidt and Housen (1987) and Melosh (1989), Bottke et al. estimated that the E-belt population should have caused 9–10 lunar basins (on average). An additional 2–3 basins should have come from within the current boundaries of the primordial main belt. Thus, in total, asteroids from the E-belt and main belt would have caused about 12 basins or so on the Moon. The numerical simulations suggest that these basin-forming events statistically should have occurred over a time-span of 400 My, starting from the E-belt destabilization event.[3] From the constraint that the youngest lunar basin (Orientale basin) formed about 3.7–3.8 Gy ago, Bottke et al. deduced that the E-belt destabilization event occurred $\sim 4.1-4.2$ Gy ago. The first of the basins formed by the E-belt should have occurred very close to this epoch (see Fig. 4 of Bottke et al., 2012).

2.1. Comparison with the lunar cratering record

Using geologic maps and the principle of superposed features, Wilhelms (1987) deduced that the Nectaris basin was approximately the 12th–14th youngest basin. Thus, given that the E-belt (and the asteroid belt) should have produced ~ 12 basins, Nectaris is likely to be either one of the first of the E-belt basins or one of the last basins formed before the destabilization of the E-belt. However, Marchi et al. (2012) found evidence that projectiles hitting Nectaris had a higher impact velocity than those hitting pre-Nectarian terrains such as the highlands or South Pole Aitken (SPA). This is consistent with Nectaris being formed within the bombardment caused by the E-belt, because the latter is characterized by higher impact velocities than in the previous period (Bottke et al., 2012). These two considerations together suggest that Nectaris might have been one of the very first basins formed as a consequence of the destabilization of the E-belt. To support further this prediction, Bottke et al. (2012) compared Marchi et al. crater counts on Nectaris terrains to the expected crater population produced by E-belt objects and found an excellent match (see Fig. 3 of Bottke et al., 2012).

Consequently, the Nice/E-belt model predicts that the age of Nectaris is 4.1–4.2 Gy, in agreement with the assumption of NI94 based on the radiometric age reported in Maurer et al. (1978), i.e., 4.1 Gy. Thus, on the left panel of Fig. 1 we assume that Nectaris is 4.1 Gy old (equivalently, we assume that Orientale is 3.7 Gy old). In this case, the curve denoting the density of craters as a function of surface age in NI94 and that predicted by the Nice/E-belt model match remarkably well over the entire 3.2–4.1 Gy period, a result that we did not expect a priori. In fact, the E-belt model was not developed to match any specific bombardment timeline, but just to complete our understanding of the coupled evolutions of giant planets and asteroids.

As explained in the previous section, however, the E-belt model depends on two parameters: the age of Orientale and the total E-belt population. The age of Orientale (whose nominal uncertainty is probably ~ 100 My around 3.75 Gy ago) shifts the E-belt cratering curve along the horizontal axis of Fig. 1. The total E-belt population (still uncertain by at least a factor of 2 despite of the arguments based on the Hungaria and main belt populations described above) shifts the E-belt cratering curve along the vertical axis. On the right panel of Fig. 1 we have varied these parameters over the range of values that allow the E-belt cratering curve to fit the data for $t>3.5$ Gy in an acceptable way. The green curves give examples of the resulting E-belt cratering curves and the shaded area illustrates the envelope of the acceptable models. This envelope gives the uncertainty of ages for a given N_1 value. We stress that the models presented in Fig. 1 also fulfill terrestrial bombardment constraints from impact spherule beds (Bottke et al., 2012) and not only the lunar cratering constraints.

Given the cumulative character of Fig. 1, we have also added the number of craters generated by E-belt objects alone to those escaping from the main belt by a combination of Yarkovsky thermal forces and resonances. We classify those objects here as main belt-derived near-Earth asteroids, or MB-NEAs for short. The crater production rate made by MB-NEAs is also uncertain. This uncertainty is included as well in the shaded area of Fig. 1, where we assume constant cratering rates, from zero up to the current value. The latter is probably an upper bound given evidence for an increase in MB-NEA flux in the last ~ 500 My ago[4] (Culler et al., 2000; Levine et al., 2005; Marchi et al., 2009).

In summary, the Nice/E-belt model agrees and supports, in broad terms, the time-line of the lunar bombardment provided by NI94, for times younger than ~ 4.1 Gy ago. Therefore, in the following, we assume the NI94 cratering over this time range, partly because it is a standard in the chronology community, but also because we do not have a good reason to change it. We now move on to discuss the bombardment rate before 4.1 Gy ago.

3. The need for a lunar bombardment spike

The bombardment rate in NI94 before 4.1 Gy has been estimated from a simple backward extrapolation of the bombardment curves calibrated on younger terrains. Although our model agrees with the NI94 bombardment curve for ages younger than 4.1 Gy, we believe that the extrapolation to older ages is not justified for the following two reasons.

3.1. Dynamical constraints from inner solar system projectile simulations

The first reason comes from dynamical considerations, namely that no source of inner solar system projectiles has yet been found that decays over 1 Gy (say from 4.5 to 3.5 Gy ago) with the rate implied by NI94 curve. For instance, consider the E-belt model, but assume that the destabilization event occurred 4.5 Gy ago. Regardless of the calibration methods discussed in the previous section, assume that the E-belt was about 20 times more populated than in Bottke et al. (2012), so that the cumulative number of craters that it produced on the Moon matches the extrapolation of NI94 curve at 4.5 Gy. As shown in Fig. 2, the model would imply far too many impacts for terrains with ages around 3–4 Gy compared to lunar crater counts.

We also note that no vertical shift of the E-belt cratering curve in Fig. 2, corresponding to a larger or smaller initial E-belt population, is capable of fitting the NI94 curve at $t \sim 3.5-4$ Gy if the E-belt destabilization event took place 4.5 Gy ago. In fact, the

[3] This timescale is much longer than Jupiter's migration timescale because the E-belt objects, after being destabilized, can remain for a considerable time on meta-stable orbits in the vicinity of the Hungaria region.

[4] Such an increase may be due to the formation of the Flora asteroid family (Nesvorný et al., 2002, 2007b).

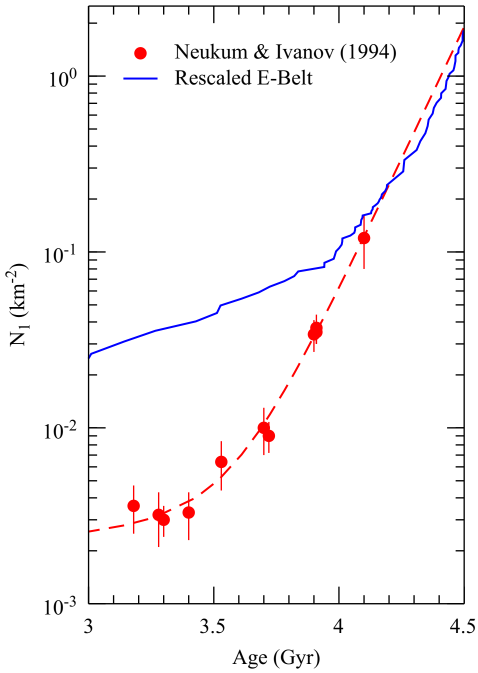

Fig. 2. The dash-red curve is the total number of craters larger than 1 km diameter per km^2 as a function of unit's age, according to NI94. The blue curve is the same, but here we assumed (i) the E-belt model, (ii) the E-belt was destabilized 4.5 Gy ago and (iii) the E-belt contained 20 times more material than used by Bottke et al. (2012). This allowed us to match the extrapolation of the NI94 curve at 4.5 Gy. Notice the overall mismatch for ages younger than 4 Gy ago. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

E-belt cratering curve is as steep as NI94 curve near 4.5 Gy, but becomes much shallower at more recent times. This is because most of the bodies surviving for several hundreds of My after the destabilization event are trapped in or near the dynamically sticky Hungaria region. These trapped bodies then leak out from the Hungaria region (developing Earth-crossing orbits) at a very slow rate. In order for the slopes of the two curves to approximately match one another in the 3.5–4.1 Gy range, the E-belt destabilization event needs to be at $t \sim 4.1$ Gy, as shown in Fig. 1.

Once could argue that the E-belt is not the appropriate source of projectiles for the bombardment of the Moon in a scenario without late giant planet migration. The problem, however, is that no appropriate source of projectiles has yet been found using the current system of planets, at least without invoking additional factors to augment the population of the late-arriving projectiles (e.g., the well-timed catastrophic disruption of a Vesta-sized asteroid residing on a Mars- or Earth-crossing orbit 3.9 Gy ago; Ćuk, 2012). In fact, Bottke et al. (2007) made a general argument against the possibility that such a source could exist.

Consider that all comprehensive lunar bombardment models need to produce the 900 and 1200 km diameter basins Imbrium and Orientale between 3.85 and 3.7 Gy ago, and no further basin formation events since that time. This requires a relatively fast decaying impacting population at ~ 3.8 Gy (unlike the E-belt example above that destabilized 4.5 Gy ago). Moreover, the decay would have to have been even faster earlier on, because population decay rates typically slow down with time. Thus, the original population would have been implausibly large, of the order of a few Earth masses of material. It is unlikely that such a population existed at the end of terrestrial planet formation, otherwise the terrestrial planets would have grown more massive.

3.2. Geochemical constraints from the Moon

The second reason for not believing the extrapolation of the NI94 curve before 4.1 Gy is provided by lunar geochemical constraints. It can be argued that the Moon's formation in a giant impact on Earth and its subsequent differentiation and magma ocean phase should have sent most iron and highly siderophile elements (HSEs) to the core. Although we have no direct samples of lunar mantle rocks, studies of HSE isotopes in derivative lunar mantle melts suggest that the Moon accreted no more than 1.7×10^{19} kg of chondritic material before its mantle became protected from incoming material by a thick crust (Walker et al., 2004; Day et al., 2007, 2010, see also Bottke et al., 2010). The lunar crust, however, is also not very rich in HSE: the amount of chondritic material delivered into the lunar crust after its formation is estimated to be 0.4×10^{19} kg (Ryder, 2002). Thus, in total, the Moon should have accreted less than $\sim 2.1 \times 10^{19}$ kg of material. Artemieva and Shuvalov (2008) estimated that, for asteroids with an impact velocity of 18 km/s (which is intermediate between the velocities of projectiles hitting the Moon before and after the destabilization of the E-belt; see Section 4) and an impact angle of 45°, only 60% of the impactor's material is effectively accreted, the rest being lost into space (e.g., see also Bottke et al., 2010). This implies that the total mass of impactors hitting the Moon since its formation was at most $\sim 3.5 \times 10^{19}$ kg.

The abundance of HSE is remarkably similar in enstatite, ordinary and carbonaceous chondrites (see Table 1 in Walker, 2009). Thus the constraints on the accreted mass reported above are presumably valid for broadly chondritic projectiles striking the Moon. However, if the bombardment had been dominated by objects derived from the mantles of differentiated bodies, the amount of HSEs delivered per unit mass would have been much smaller. In other words, the mass accreted by the Moon after its formation could have been higher than estimated above. We consider that this possibility is unlikely because: (i) achondritic meteorites are rare and (ii) the SFD of the craters on the oldest lunar terrains suggests that the projectiles had a SFD similar to main belt asteroids (Strom et al., 2005), which would be surprising if the objects had predominantly a different physical nature; (iii) the HSEs in the Moon and terrestrial mantle are in chondritic proportions, whereas they would be fractionated relatively to each other if they had been delivered predominantly by achondritic objects. For these reasons, it is standard practice to use HSE abundances as indicators of the accreted massed assuming chondritic proportion (e.g., Ryder, 1990; Walker, 2009; Day et al., 2007, 2010).

Below, we compare this value to the total mass of projectiles that should have hit the Moon in the bombardment history of NI94. This estimate is done in two steps.

Step I: First, we extrapolated the NI94 curve to 4.5 Gy, the approximate time of the Moon's formation (Kleine et al., 2009). This yielded the number of craters larger than 1 km diameter per surface square kilometer $N_1 = 1.9$. The relationship between N_1 in NI94 and N_{20} in Marchi et al. (2012) (respectively, the number of craters larger than 1 and 20 km per surface square kilometer) is ~ 1400. Assuming this ratio, the NI94 curve, extrapolated to 4.5 Gy implies $N_{20} = 1.3 \times 10^{-3}$.

Step II: Next, we established a general procedure to link N_{20} to the total mass of the corresponding projectile population. The procedure is as follows. First, we computed the impactor size D_{20} corresponding to a crater of 20 km. For this, we use the correction from final-to-transient crater as reported in Marchi et al. (2011) and we adopt the Pi-scaling group law for hard rock in the formulation of Schmidt and Housen (1987) and Melosh (1989), assuming an impact velocity of 18 km/s. Second, we assume that the projectile SFD is the same as the main belt SFD (Strom et al., 2005). Given the numbers of projectiles larger than D_{20} (which is the product between the N_{20} value and the surface of the Moon in km^2), we estimate the size $D_{\max}$ of the largest projectile that should have impacted the lunar surface. Given this information we finally compute the total projectile mass. For this, we assumed a projectile density of $\rho = 2.6$ g/cm^3, a scaled value designed to account for the mass integral of the entire main belt SFD over all compositions, with the estimated total mass of the asteroid belt given by Krasinsky et al. (2002). Note that because $D_{\max}$ changes with N_{20}, the total mass of the projectiles hitting the Moon does not scale linearly with N_{20}.

Applying these two steps, we estimate that the total mass of the projectiles hitting the Moon since its formation in the NI94 bombardment history is 1.3×10^{20} kg. This is a factor of 4 larger than the upper bound on the total mass delivered to the Moon throughout its history, as constrained above from the lunar HSE abundances.

3.3. Summary

The two reasons discussed above suggest the need for a break, or inflection point, in the bombardment curve at sometime in the 4.1–4.2 Gy interval. While the bombardment rate just before the break had to be smaller than after the break, the impact flux probably increased from that point backwards in time until the Moon-formation event. This discontinuity defines the signature of a lunar cataclysm.

In the next section we attempt to derive a plausible lunar impact rate in the 4.1–4.5 Gy period using both dynamical considerations and the constraints provided by the abundance of lunar HSEs.

4. The nature of the lunar bombardment before the cataclysm

The bombardment of the terrestrial planets in the early epochs of the solar system, well before the lunar cataclysm, was presumably caused by remnant planetesimals from the original disk that formed the planets. The best available computer simulations of the terrestrial planet accretion process are those reported in Hansen (2009) and Walsh et al. (2011), mainly because they can satisfactorily reproduce the mass distribution and orbital characteristics of the terrestrial planets.

In order to understand the dynamics of planetesimals leftover from the planet accretion process, we considered four of the most successful simulations from Walsh et al. (2011). In two of the simulations, the terrestrial planets reached completion and stabilization in ~ 30 My (simulations A). In the other two they stabilized at ~ 50 My (simulations B). This is acceptable because the time required for the formation of the Earth is only modestly constrained by radioactive chronometers (see Kleine et al., 2009, for a review). A timescale of 30 to 50 My is considered as a realistic timescale, although ~ 100 My has also been suggested (e.g., Allègre et al., 1995; Touboul et al., 2007). The simulations of Hansen and Walsh et al., however, always complete the formation of the terrestrial planets well before the latter time.

For the simulations A and B, we took the orbital distribution of the planetesimals surviving at 30 or 50 My, respectively. We cloned the planetesimals by randomizing the orbital angles (mean anomaly, longitude of node and of perihelion). This gave us four sets with a total of 2000 particles each.

The final synthetic terrestrial planets in the Walsh et al. simulations form a system relatively similar but not identical to our own. Thus, to study the dynamical decay of the planetesimal populations in the actual solar system, we need to substitute the synthetic planets with the "real" ones.

The problem is that eccentricities and inclinations of the terrestrial planets before giant planet migration (at the time of the lunar cataclysm) are uncertain. Brasser et al. (2009) argued that the orbits of the terrestrial planets might have been significantly more circular and less inclined than the current orbits. They could not exclude the possibility, however, that the terrestrial planets' eccentricities and inclinations were already comparable to the current ones. Thus, for each of the four sets of planetesimals we did two integrations. For the first, we assumed that the terrestrial planets had their current orbits. For the second, we put the terrestrial planets on orbits with their current semimajor axes but with eccentricities and inclinations equal to zero.

Our integrations covered 400 My (i.e., the time-span between the Moon forming event and the onset of the lunar cataclysm, assuming that they happened respectively 4.5 and 4.1 Gy ago). At each output time, we then computed the collision probability and impact velocity of each particle with the Earth ($c_p(t)$) using the algorithm described in Wetherill (1967): the semimajor axis, eccentricity and inclination of the particle and the Earth were kept equal to the values registered in the output, while the angles (mean anomaly, longitude of perihelion and of the node) were randomized over 360°. The effect of the Earth's gravitational focusing was also taken into account, given the relative velocities provided by the simulations. The impact probabilities of all particles at a given time were then summed, obtaining a total collision probability ($C_E(t) = \sum_p c_p(t)$) at the considered time. The collision probability with the Moon $C_M(t)$ was assumed to be a constant fraction (1/20) of $C_E(t)$. The actual value of this ratio (which depends on the velocity of the projectiles) is not important, as we are only interested here in the time evolution of C_M and not its absolute value. In principle the C_M/C_E ratio decreases with time as the Moon gets farther from the Earth following its tidal evolution. But in practice Moon's migration is very fast at the very beginning and then slows down considerably, so that the assumption that C_M/C_E is constant is a classical, reasonable approximation.

The tabulated function $C_M(t)$ describes the time evolution of the lunar impact rate in the considered simulation. It was then interpolated with a function of type $\exp(-(t/t_0)^\beta)$ (Dobrovolskis et al., 2007) to obtain a smooth, analytical function. The decay is obviously different from simulation to simulation, but we found it to be confined between two functions with ($t_0 = 10$ My, $\beta = 0.5$) and ($t_0 = 3$ My, $\beta = 0.34$). At 400 My, the values of these two functions have a ratio of 2.5.

Recall that the total mass accreted by the Moon since it differentiated, according to constraints from lunar HSEs, is $\lesssim 3.5 \times 10^{19}$ kg. Given the value of N_{20} for the Nectaris basin (8.66×10^{-5} km^{-2}: Marchi et al., 2012) and applying the procedure explained in Section 3.2, we find that the net projectile mass that has hit the Moon since 4.1 Gy ago is 2×10^{18} kg. By subtracting this value from $\sim 3.5 \times 10^{19}$ kg, we conclude that $\lesssim 3.3 \times 10^{19}$ kg of projectiles should have hit the Moon between 4.1 and 4.5 Gy ago.

Taking the functions that bracket the decay of the impact rate, we normalized both of them so that the total mass hitting the Moon in the 4.1–4.5 Gy period was 3.3×10^{19} kg. The correspondence between N_{20} and the mass hitting the Moon was computed using the procedure described in Section 3.2.[5]

Fig. 3 summarizes our results. The red curves on the left panel shows our estimate of the time evolution of the lunar impact rate.

[5] In agreement with the results of Marchi et al. (2012), we used an impact velocity of 11 km/s instead of 18 km/s as stated in Section 3.2 for the computation of the projectile size needed to make a 20 km crater.

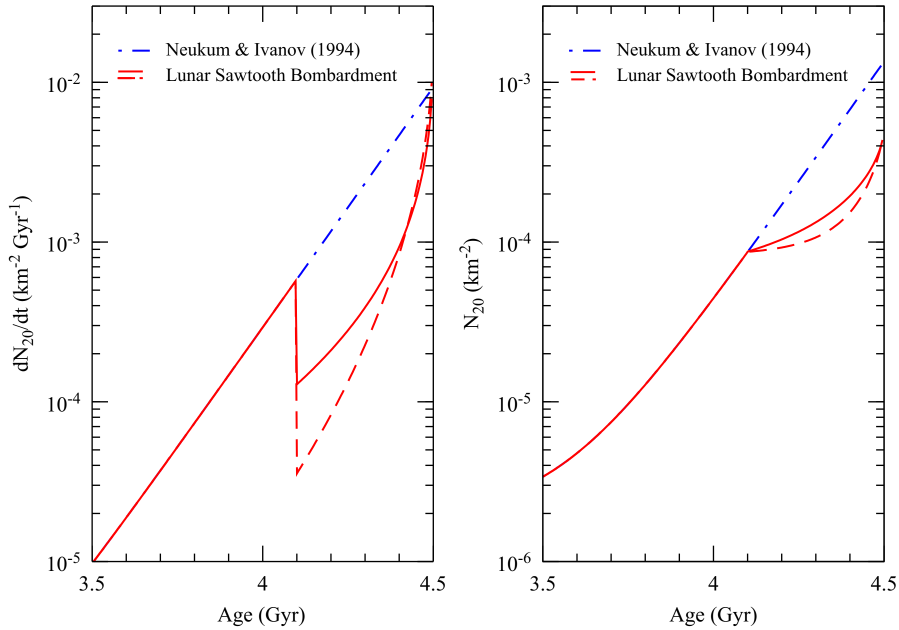

Fig. 3. The timeline of lunar bombardment. The blue dash-dotted line is the exponential decay assumed by NI94. The red curves show our results combining a post-accretion bombardment of leftover planetesimals in the 4.1–4.5 Gy time range and the asteroid main belt and E-belt bombardments for $t < 4.1$ Gy. The solid and dashed curves for $t > 4.1$ Gy correspond to the two analytic functions that bracket the early decay of the cratering rate, as discussed in the text. The left panel shows the bombardment rate as a function of time (measured in number of craters larger than 20 km produced per km^2 and per Gy). The right panel shows the cumulative bombardment suffered by a given terrain as a function of its age (measured in number of craters larger than 20 km per km^2, i.e., N_{20}). On the left panel, the equations of for the curves are the following. For $t < 4.1$ Gy : $dN_{20}/dt = 2.7 \times 10^{-16} e^{6.93t} + 5.9 \times 10^{-7}$; for $t > 4.1$ Gy and the solid curve: $dN_{20}/dt = 2.5 \times 10^{-2} e^{-[(4.5-t)/0.003]^{0.34}}$; for the red dashed curve: $dN_{20}/dt = 2.0 \times 10^{-2} e^{-[(4.5-t)/0.01]^{0.5}}$; the time t is measured in Gy. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These curves have a *sawtooth* profile, with the uptick at 4.1 Gy representing the onset of the lunar cataclysm. This profile is very different than the continuous exponential decay of NI94 for ages older than 4.1 Gy, as shown by the blue line. The right panel shows the cumulative lunar impact flux as measured by the density of craters expected on a given surface as a function of its age. The curves were obtained by integrating the values reported on the left panel from 0 to t for all values of t.

5. Discussion and conclusions

We have taken our best models of the early solar system evolution, determined the impact flux on the Moon over time and then calibrated these results using the existing dynamical, geochemical, and crater density constraints.

We infer that the evolution of the lunar bombardment rate is somewhat intermediate between the two end-member views in this historical controversy. Our model bombardment rate from 4.1 to 3.5 Gy ago agrees with the exponential decay illustrated by NI94, the champions of the no-cataclysm view. We find that it is impossible, however, to extrapolate their exponential flux backward in time before 4.1 or possibly 4.2 Gy. We believe a discontinuity in the evolution of the bombardment rate, or a lunar cataclysm, is the easiest way to match constraints. The timeline of the Moon's bombardment that emerges from our study has a sawtooth profile, with a moderate uptick at 4.1–4.2 Gy (see Fig. 3, left panel). This stands in sharp contrast with the prominent impact spike usually shown in sketches of the lunar cataclysm; instead it is in broad agreement with the scenario of "weak cataclysm" promoted in Fig. 3 of Hartmann et al. (2000).

Our impact flux model predicts the lunar bombardment from 4.1 Gy ago – which includes the cataclysm caused by the destabilization of the main asteroid belt ($\sim 15-25\%$ of cataclysm impactors) and E-belt ($\sim 75-85\%$ of cataclysm impactors) – accounts for approximately 25% of the total bombardment suffered by the Moon since it formed. This is in agreement with the total number of basins on the Moon (~ 50), of which only $\sim 12-14$ are Nectarian and early-Imbrian (i.e., younger than ~ 4.1 Gy). We note that we could be underestimating the number of basins because some ancient basins have probably been erased (Frey and Romine, 2011). The best estimate at present is that the total number of basins probably does not exceed ~ 60 (Frey, private communication), not far from our expectations for the combined leftover planetesimal and E-belt models. We stress that basin formation is necessarily a stochastic process which can deviate from probabilistic expectations due to small number statistics. Assuming Poisson statistics (i.e., the error bar on N events is $\sqrt{N}$), the number of basins formed in our model since the destabilization of the E-belt is 12 ± 4, while the total number of basins is 45 ± 7.

Large portions of the lunar highlands have a crater density that is about twice that of Nectaris (Strom, 1977; Marchi et al., 2012), with a value of $N_{20} = 1.73 \times 10^{-4}$. According to the cumulative bombardment shown in Fig. 3, this would imply that these portions of highlands started to retain craters about 4.38–4.42 Gy ago, ages that are consistent with recent estimates of the timescale for the thickening of the lunar lithosphere (Meyer et al., 2010). This age also approximates the closure age of the crust, as derived from zircons that crystallized in the remaining urKREEP residue of the lunar magma ocean 4.38–4.48 Gy (Nemchin et al., 2009; Taylor et al., 2009). Similarly, the value of N_{20} for the SPA floor is 1.36×10^{-4} (Marchi et al., 2012). This implies that craters started to accumulate on SPA since 4.33–4.39 Gy ago. This age should be considered as a lower bound for the formation age of SPA, because the basin's floor might have solidified only after some time; it clearly shows that SPA is an old basin, which definitely predates the cataclysm event.

The sawtooth-like bombardment timeline has important implications for Earth's habitability. In the no-cataclysm view, the Earth was increasingly hostile to life going back in time, as the bombardment exponentially increased. In the classic view of the lunar cataclysm, the prominent impact spike 3.8–3.9 Gy ago conceivably sterilized the Earth by vaporizing all the oceans and thereby creating a steam atmosphere (Maher and Stevenson, 1988; however see Abramov and Mojzsis, 2009). In our sawtooth view, big impactors hit over an extended period, with more lulls and therefore more opportunities for the Hadean-era biosphere to recover. Perhaps in this scenario, life formed very early and has survived in one form or another through the lunar cataclysm.

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References

Abramov, O., Mojzsis, S.J., 2009. Microbial habitability of the Hadean Earth during the late heavy bombardment. Nature 459, 419–422.
Allègre, C.J., Manhès, G., Gopel, C., 1995. Geochim. Cosmochim. Acta 59, 2445.
Artemieva, N.A., Shuvalov, V.V., 2008. Sol. Syst. Res. 42, 329.
Bottke, W.F., Durda, D.D., Nesvorný, D., et al., 2005. Icarus 175, 111.
Bottke, W.F., Levison, H.F., Nesvorný, D., Dones, L., 2007. Icarus 190, 203.
Bottke, W.F., Vokrouhlický, D., Minton, D., Nesvorný, D., Morbidelli, A., Brasser, R., Simonson, B., Levison, H.F., 2012. Nature 485, 78.
Brasser, R., Morbidelli, A., Gomes, R., Tsiganis, K., Levison, H.F., 2009. Astron. Astrophys. 507, 1053.
Brož, M., Vokrouhlický, D., Morbidelli, A., Nesvorný, D., Bottke, W.F., 2011. Mon. Not. R. Astron. Soc. 414, 2716.
Chapman, C.R., Cohen, B.A., Grinspoon, D.H., 2007. Icarus 189, 233.
Charnoz, S., Morbidelli, A., Dones, L., Salmon, J., 2009. Icarus 199, 413.
Cohen, B.A., Swindle, T.D., Kring, D.A., 2000. Support for the Lunar Cataclysm Hypothesis from Lunar Meteorite Impact Melt Ages. Science 290, 1754–1756.
Ćuk, M., 2012. Chronology and sources of lunar impact bombardment. Icarus 218, 69–79.
Culler, T.S., Becker, T.A., Muller, R.A., Renne, P.R., 2000. Science 287, 1785.
Day, J.M.D., Pearson, D.G., Taylor, L.A., 2007. Science 315, 217.
Day, J.M.D., Walker, R.J., James, O.B., Puchtel, I.S., 2010. Earth Planet. Sci. Lett. 289, 595.
Dobrovolskis, A.R., Alvarellos, J.L., Lissauer, J.J., 2007. Icarus 188, 481.
Fassett, C.I., Head, J.W., Kadish, S.J., Mazarico, E., Neumann, G.A., Smith, D.E., Zuber, M.T., 2012. Lunar impact basins: stratigraphy, sequence and ages from superposed impact crater populations measured from Lunar Orbiter Laser Altimeter (LOLA) data. J. Geophys. Res. (Planets) 117, (E00H06), 13pp, 〈http://dx.doi.org/10.1029/2011JE003951〉.
Frey, H.V., Romine, G.C., 2011. Lunar and Planetary Institute Science Conference Abstracts, 42, 1190.
Galenas, M.G., Gerasimenko, I., James, O.B., Puchtel, I.S., Walker, R.J., 2011. Lunar and Planetary Institute Science Conference Abstracts, 42, 1413.
Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., 2005. Nature 435, 466.
Hartmann, W.K., 1975. Icar 24, 181.
Hartmann, W.K., Ryder, G., Dones, L., Grinspoon, D., 2000. Origin of the Earth and Moon, p. 493.
Hartmann, W.K., 2003. Megaregolith evolution and cratering cataclysm models - Lunar cataclysm as a misconception (28 years later). Meteoritics and Planet. Sci. 38, 579–593.
Hansen, B.M.S., 2009. Astrophys. J. 703, 1131.
Joy, K.H., Zolensky, M.E., Nagashima, K., Huss, G.R., Ross, D.K., McKay, D.S., Kring, D.A., 2012. Science 336, 1426.
Kleine, T., Touboul, M., Bourdon, B., et al., 2009. Geochim. Cosmochim. Acta 73, 5150.
Krasinsky, G.A., Pitjeva, E.V., Vasilyev, M.V., Yagudina, E.I., 2002. Hidden mass in the asteroid belt. Icarus 158, 98–105.
Kring, D.A., Cohen, B.A., 2002. J. Geophys. Res. 107, 5009.
Levine, J., Becker, T.A., Muller, R.A., Renne, P.R., 2005. Geophys. Res. Lett. 32, 15201.
Levison, H.F., Dones, L., Chapman, C.R., et al., 2001. Icarus 151, 286.
Maher, K.A., Stevenson, D.J., 1988. Impact frustration of the origin of life. Nature 331, 612–614.
Marchi, S., Mottola, S., Cremonese, G., Massironi, M., Martellato, E., 2009. Astrophys. J. 137, 4936.
Marchi, S., Massironi, M., Cremonese, G., Martellato, E., Giacomini, L., Prockter, L., 2011. Planet. Space Sci. 59, 1968.
Marchi, S., Bottke, W.F., Kring, D.A., Morbidelli, A., 2012. Earth Planet. Sci. Lett. 325, 27.
Marzari, F., Weidenschilling, S.J., 2002. Icarus 156, 570.
Maurer, P., Eberhardt, P., Geiss, J., et al., 1978. Geochim. Cosmochim. Acta 42, 1687.
Melosh, H.J., 1989. Impact Cratering: A Geologic Process. Oxford University Press.
Meyer, J., Elkins-Tanton, L., Wisdom, J., 2010. Icarus 208, 1.
Minton, D.A., Malhotra, R., 2011. Secular resonance sweeping of the main asteroid belt during planet migration. Astrophys. J. 732, 53.
Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R., 2005. Nature 435, 462.
Morbidelli, A., 2010. C. R. Phys. 11, 651–659.
Morbidelli, A., Brasser, R., Gomes, R., Levison, H.F., Tsiganis, K., 2010. Astrophys. J. 140, 1391.
Nemchin, A.A., Pidgeon, R.T., Healy, D., Grange, M.L., Whitehouse, M.J., Vaughan, J., 2009. J. Mech. Phys. Solids 44, 1717–1734.
Nesvorný, D., Morbidelli, A., Vokrouhlický, D., Bottke, W.F., Brož, M., 2002. Icarus 157, 155.
Nesvorný, D., Vokrouhlický, D., Morbidelli, A., 2007a. Astrophys. J. 133, 1962.
Nesvorný, D., Vokrouhlický, D., Bottke, W.F., Gladman, B., Häggström, T., 2007b. Icarus 188, 400.
Neukum, G., Wilhelms, D.E., 1982. Lunar and Planetary Institute Science Conference Abstracts, 13, 590.
Neukum, G., 1983. Habilitation Dissertation for Faculty Membership. University of Munich.
Neukum, G. Ivanov, B.A., 1994. In Hazards due to Comets and Asteroids, p. 359, T. Gehrels ed. University Arizona Press.
Norman, M.D., Duncan, R.A., Huard, J.J., 2010. Geochim. Cosmochim. Acta 74, 763.
Papanastassiou, D.A., Wasserburg, G.J., 1971a. Earth Planet. Sci. Lett. 12, 36.
Papanastassiou, D.A., Wasserburg, G.J., 1971b. Earth Planet. Sci. Lett. 11, 37.
Ryder, G., 1990. EOS Trans. Am. Geophys. Union 71, 313.
Ryder, G., 2002. J. Geophys. Res. 107, 5022.
Schmidt, R.M., Housen, K.R., 1987. Int. J. Inf. Eng. 5, 543.
Sekanina, Z., 1984. Icarus 58, 81.
Stöffler, D., Ryder, G., 2001. Space Sci. Rev. 96, 9.
Strom, R.G., 1977. Phys. Earth Planet. Inter. 15, 156.
Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A., 2005. Science 309, 1847.
Taylor, D.J., McKeegan, K.D., Harrison, T.M., Young, E.D., 2009. Geochim. Cosmochim. Acta Suppl. 73, 1317.
Tera, F., Papanastassiou, D.A., Wasserburg, G.J., 1974. Earth Planet. Sci. Lett. 22, 1.
Touboul, M., Kleine, T., Bourdon, B., Palme, H., Wieler, R., 2007. Nature 450, 1206.
Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F., 2005. Nature 435, 459.
Turner, G., Cadogan, P.H., Yonge, C.J., 1973. Nature 242, 513.
Walker, R.J., Horan, M.F., Shearer, C.K., Papike, J.J., 2004. Earth Planet. Sci. Lett. 224, 399.
Walker, R.J., 2009. Chem. Erde Geochem. 69, 101.
Walsh, K.J., Morbidelli, A., Raymond, S.N., O'Brien, D.P., Mandell, A.M., 2011. Nature 475, 206.
Wasserburg, G.J., Papanastassiou, D.A., 1971. Earth Planet. Sci. Lett. 13, 97.
Wetherill, G.W., 1967. J. Geophys. Res. 72, 2429.
Wilhelms, D.E., 1987. The Geologic History of the Moon. (U.S. Geol. Surv. Prof. Pap., 1348.).