THE SAWTOOTH-LIKE TIMELINE OF THE FIRST BILLION YEAR OF LUNAR BOMBARDMENT.

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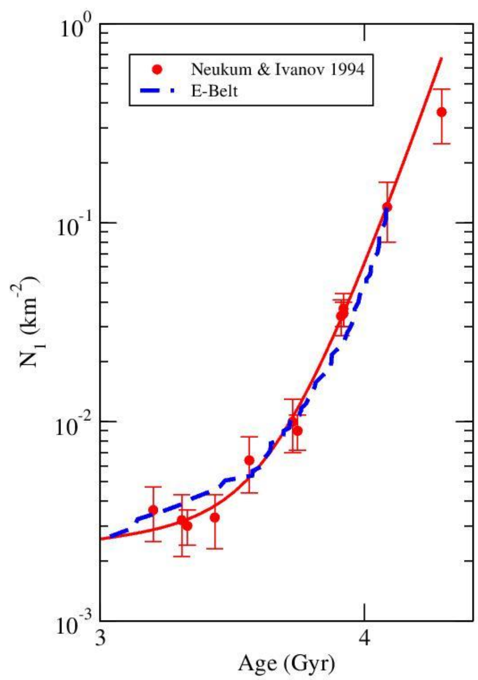
Introduction: Two radically different views of the Moon's bombardment history can be found in the literature: one describing a smooth exponential decline of the bombardment rate from 4.5 to 3.6 Ga ago [1] and the other arguing for a prominent impact spike about 3.9 Ga ago [2]. Both scenarios claim to be consistent with crater counts on lunar terrains of "known" radiometric ages. In reality, however, only the youngest units, starting with the Imbrium basin ~3.8-3.9 Ga ago, have well established radiometric ages, whereas the ages of older basins, like Nectaris and Serenitatis, are subjects of debate [3]. The view arguing for a smooth exponential decline assumes that the age of Nectaris is ~4.1 Ga, while the view arguing for an impact spike assumes that its age is ~3.9 Ga. This younger age implies a steeper decline of the bombardment rate in the 3.9-3.7 Ga period which, when extrapolated back to 4.5 Ga, requires am unrealistic number of starting projectiles: hence the need for an impact spike.

In this abstract, we revisit the problem from a combination of theoretical considerations (by looking at plausible source of projectiles and their dynamical evolutions) and calibrations on constraints. Our results support a view which is somewhat intermediate between the two endmember views described above. In fact, we argue for the need of an impact spike, but as early as ~4.1 Ga ago and not as prominent as in [2].

The Nice model and the E-belt: The Nice model [4,5] 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. Such a change is needed in order to explain the current structure of the outer Solar System, but the time when it occurred is not known a priori (see [6] for a review). The most recent and interesting development of the Nice model is the E-belt concept [7], which stems from the realization that the current inner boundary of the asteroid belt (~2.1 AU) is set by the nu6 secular resonance whose existence is specifically related to the current orbits of Jupiter and Saturn. Before the giant planets changed their orbital configuration, Jupiter and Saturn were closer to one another and were on more circular orbits; this meant the nu6 resonance was not present. Hence the asteroid belt could extend closer to Mars (i.e. down to 1.7-1.8 AU). This putative E-belt population between 1.7-2.1 AU is now nearly gone, with the survivors making up the Hungaria asteroids.

The original population in this region is calibrated in two independent ways, leading to very similar population estimates. The Size Frequency Distribution (SFD) of the E-belt objects is assumed to be the same as in the current main asteroid belt. With these settings, when the E- and main belts were destabilized by giant planet migration, about 12 basins formed on the Moon [7] over a period of ~400 Ma,. Knowing that the last basin on the Moon (Orientale) formed ~3.7 Ga ago, this implies that the ~12th from the last basin (i.e. Nectaris) formed about ~4.1 Ga ago, in agreement with [1]. Moreover, the number of craters per unit area formed since the destabilization of the E-belt is consistent with crater counts on Nectaris. And finally, the decay rate of the bombardment rate since the destabilization of the E-belt is in very good agreement with the bombardment decline in [1] (see Fig. 1). In summary, the Nice model agrees and supports the view of [1] for times up to ~4.1 Ga ago.



Red curve: the total number of craters larger than 1km per km^2 as a function of unit's age, according to [1]. Dash-blue: the same, for the E-belt model [7]. Notice the almost perfect match between 3.4 and 4.1 Ga.

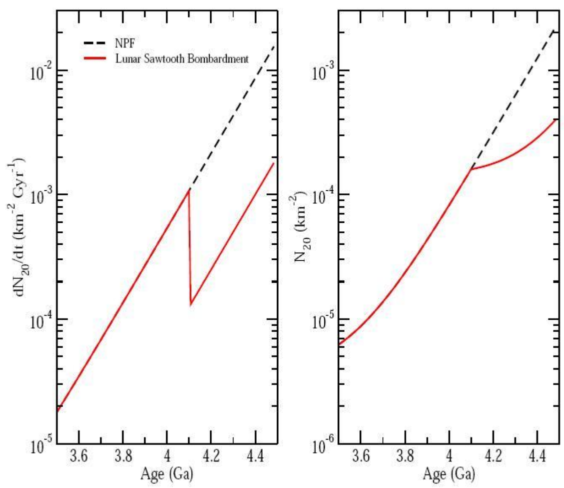
The need for a bombardment spike: The bombardment rate in [1] before 4.1 Ga is estimated by a simple backward extrapolation of the bombardment rate inferred in the 3.4-4.1 Ga period. It is possible, however, that this extrapolation is not justified: (i) no source of projectiles has ever been shown to be able to decay over ~1 Gy with the rate implied in [1]; (ii) if the extrapolation were correct, the total mass accreted by the Moon since its formation would have been ~5 times larger than that inferred from the Highly Siderophile Element (HSE) content of the Lunar mantle (1.7×10^{19}kg, [8]).

In agreement with our improved understanding of the early Solar System evolution, we postulate that the Moon experienced two distinct bombardments: (a) a post-accretion bombardment, due to the planetesimals leftover from the terrestrial planet formation process and (b) a late bombardment, triggered at ~4.1 Ga by the displacement of the giant planets orbits and the destabilization of the E-belt. Here we assume for simplicity that the decay rate of the post-accretion bombardment was the same as that of the late bombardment (a better estimate of the decay rate of the early bombardment is in progress, from recent simulations of terrestrial planet formation [9]). Thus, we are left with only a single free parameter, which is the total intensity of the post-accretion bombardment. The latter is calibrated by total amout of material accreted by the Moon since its formation, as constrained by the Lunar HSE abundance, though here we assume that most of the early projectile mass reaches and is mixed into the lunar mantle through a presumably thin conductive lid.

Conclusions: The resulting timeline of lunar bombardment is reported in Fig. 2, both in differential and cumulative forms. The differential view suggests that, rather than a impact spike, the timeline of the Moon bombardment has a sawtooth profile. The cumulative view shows that the bombardment since 4.1 Ga ago, including the late bombardment caused by the destabilization of the E-belt, accounts for about 1/3 of the total bombardment suffered by the Moon since its existence. This is in agreement with the total number of basins on the Moon (~40), of which only ~12 are Nectarian and post-Nectarian (i.e. younger than ~4.1 Ga). We note that this could be an underestimate because some ancient basins have probably been erased.

Large portions of the lunar highlands have a crater density that is about twice of that of Nectaris [10]. According to the cumulative bombardment shown in Fig. 2, this would imply that these portions of highlands started to retain craters about 4.35 Ga ago, consistent with recent estimate of the timescale for the thickening of the lunar lithosphere [11]. This age also matches the closure age of the crust, as derived from the model ages for KREEP (P. Spudis, pers. comm.) This suggests that the lunar lithosphere could retain the imprint of basins earlier than the imprint of small craters.

The sawtooth-like bombardment timeline has profound implications for Earth's habitability. In the view of [1], the Earth was increasingly hostile to life going back in time, as the bombardment raised exponentially. In the view of [2] the prominent impact spike 3.9 Ga ago might have sterilized the Earth. In the sawtooth view, the bombardment rate was perhaps never exceptionally high, though big impactors did occur over an extended period. Life might have formed early in the Earth history and survived from that time.



The timeline of the Moon bombardment. Black dashed (labeled NPF): the view in [1]. Red curve: our results combining a post-accretion bombardment and the late E-belt bombardment. The left panel shows the bombardment rate as a function of time; the right panel shows the cumulative bombardment suffered by a terrain as a function of its age. The unit on the vertical axes is the number of craters larger than 20km per km^2.

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