TWO POPULATIONS OF EARLY LUNAR IMPACTORS AS RECORDED IN ITS ANCIENT CRATER POPULATIONS.

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Introduction: The earliest bombardment history of the Moon potentially provides powerful constraints for solar system evolution models.

The density of craters on lunar terrains of different ages have been used to study the temporal evolution of the lunar impactor flux. According to these studies [1,2,3], the bombardment of the early Moon experienced a rapid but smooth decay as the leftovers of planetary accretion were gradually eliminated. This declining bombardment phase ended about ~3.7 Ga ago.

This view contradicts the analyses of Apollo lunar samples [4,5] and lunar meteorites [6], which collectively show a clustering of impact-reset Ar-Ar ages and extensive crustal U-Pb mobilization at 3.8-3.9 Ga. These data suggest the Moon was affected by a spike of impacts that would have lasted for a few tens to hundreds of My. This is often referred to as the lunar cataclysm (LC).

If a cataclysm really occurred, it could have left traces in the crater size-frequency distribution (SFD) resulting from impactors leftover from planetary accretion and from impactors responsible for the cataclysm. In order to investigate the above issues, we undertook new lunar crater counts on old lunar terrains.

Terrain choice and crater counts: Crater identification and counts have been performed on digital terrain model (DTM) produced by the Lunar Orbiter Laser Altimeter (LOLA) [7] on board the Lunar Reconnaissance Orbiter. The resolution of the DTM was 64-pixel-per-degree. We analyzed three major regions.

The first region corresponds to a wide portion of the Pre-Nectarian terrains on the northern farside (PNT hereinafter). The second region includes Pre-Nectarian terrains on the floor of the largest impact basin on the Moon, South Pole-Aitken basin (SPAT hereinafter). Both regions are among the oldest ones on the Moon. The third region is made of a part of Nectaris basin floor, its rim regions, and a portion of its ejecta blanket (NBT hereinafter). Nectaris is a benchmark basin used to define time periods on the Moon [8]. It is also the oldest, closest basin to the Apollo 16 landing site in the lunar highlands and has an estimated radiometric age of 3.9 to 4.1 Ga [9,10].

The first challenge is to define geological units that can be used for cratering studies. For instance, most of the Pre-Nectarian terrains are covered by several ejecta blankets from different basins, therefore they may not correspond to an unique age. Nevertheless, empirical estimate of the relevant basins' ejecta thickness [11] suggest they were not able to efficiently obliterate D>15 km craters. We also examined multiple areas within the PNT, SPAT, and NBT terrains to determine if endogenous processes, largely connected to the obliteration of pre-existing craters by the emplacement of lava flows, influenced our results. No effects were found as long as we avoided obvious mare regions on the basin floors. This analysis also showed that the (crypto)mare present in the central part of the SPA basin floor did not significantly affect the D>15 km crater population relative to the peripheral parts of said floor. Finally, by comparing several PNT regions, we determined that large secondary craters did not significantly influence our crater counts in any one of them. The resulting crater SFDs are shown in Figure 1 A, B.

Discussion: Several points of interest stand out from Fig. 1. First, PNT has a higher surface crater density than SPAT for 15<D<60 km. On the other hand, PNT and SPAT are indistinguishable in the range 60<D<150 km. NBT crater density is lower than both SPAT and PNT, as expected given its presumed relatively younger age.

These observations provide us with several curiosities. For example, it is difficult to explain why PNT and SPAT differ for 15<D<60 km yet are within error bars for 60<D<150 km. Our immediate concern was that the overlap was due to crater saturation effects [12]. Using a crater formation code that could model how crater saturation would affect these terrains [13], we determined PNT and SPAT are not saturated.

If the crater SFDs are not saturated, they must reflect the impactors that formed them. The conclusions above imply that the observed crater SFDs reflect their respective impactor SFDs. Therefore, in the light of the higher crater density of PNT, it must be the oldest among the three terrains considered here. Interestingly, all the crater SFDs in a log-log plot are well reproduced by two-sloped distributions up to D=150 km (Fig. 1 C). The cumulative slopes (in log-log plot) derived by best fitting are -1.25±0.03 and -2.6±0.1 for small and large D, respectively. The substantial increase in the slope for small craters with respect to large ones produces a characteristic elbow whose corresponding crater size (D_{elbow}) varies from one distribution to another. Using Monte Carlo simulations we determined that the resulting D_{elbow} is ~47, ~61, ~67 km for PNT, SPAT and NBT, respectively.

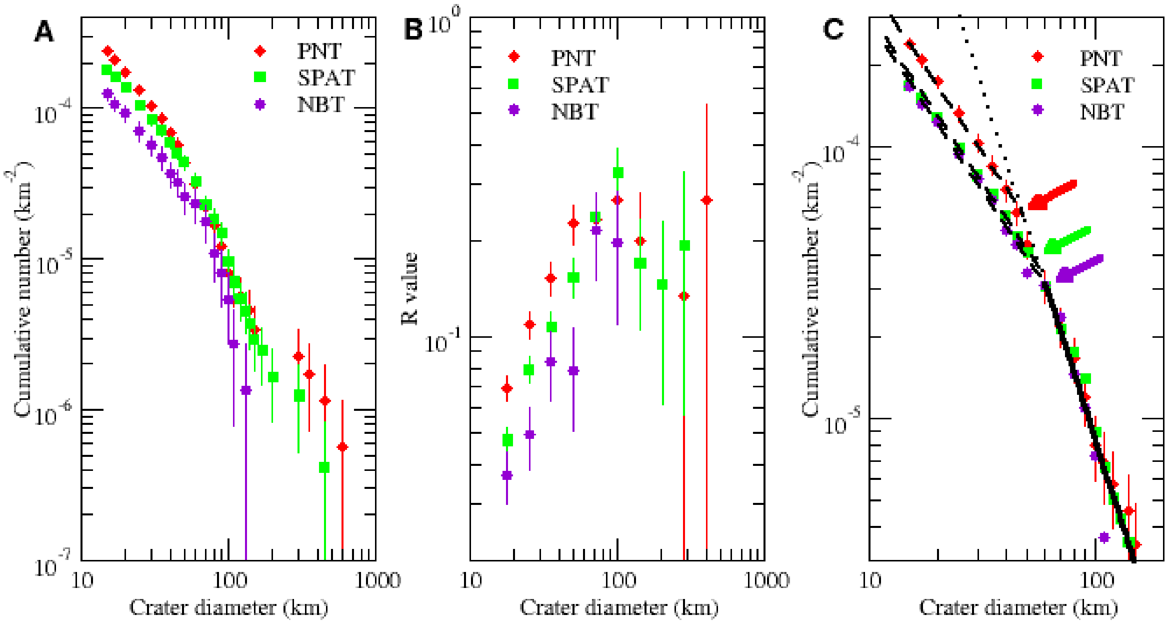

Figure 1: ***A-B:*** *Observed crater SFDs on PNT, SPAT and NBT expressed in cumulative and R-values, respectively.* ***C:*** *Rescaled crater SFDs.* The solid and dashed curves indicate the two-sloped branches of the distributions, and the arrows indicate the approximate positions of the intersection points (see text).

This finding suggests the elbow position shifted to larger sizes from older terrains (PNT) to younger ones (NBT).

Conclusions: We believe the simplest way to explain the observed similarity of the shapes of the crater SFDs is if the impactor SFD stayed constant but the impact velocity increased on the youngest terrains. Higher velocities would boost the sizes of the craters on NBT terrains, thereby collectively shifting its crater SFD to larger values. To test our hypothesis we attempted to reproduce via Monte Carlo simulations the PNT, SPAT and NBT crater SFDs assuming that they recorded, in sequence, two impact populations having distinct velocities, each producing craters with distinct values of D_{elbow}. The combination of these two impacting populations that best fits the observations is achieved by assuming that i) NBT was hit uniquely by an impactor population producing D_{elbow}~60 km, that we call ``late population" and ii) PNT and SPAT record, in addition to this late population, an ``early population" producing D_{elbow}~45 km.

Overall the early population accounts for 48% and 32% of the craters $D \geq 15$ km observed on PNT and SPAT, respectively. The crater SFDs obtained by this combination of impacting populations pass through the error bars of all the data on all terrains.

In the light of these findings, we conclude that the observed shift in the elbow is most likely due to a variation in the mean impact velocity. According to the Pi-group crater scaling law [14], the crater size scales as $v^{0.44}$, where v is the impact velocity. Therefore, we estimate that the elbow shift from the early to the late population corresponds to a variation of the impact velocity of a factor of ~2 $(=(60/45)^{1/0.44})$. Such an increase in the impact velocity implies a major change to the impactor population. As such, it has major implications for the early history of the solar system. This dramatic velocity increase is consistent with the existence of a lunar cataclysm and potentially with a late reconfiguration of giant planet orbits, which strongly modifies the source of lunar impactors.

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