NEW OBSERVATIONAL EVIDENCE OF NONUNIFORM CRATERING OF THE MOON.

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Introduction: Nonuniformity of cratering rates on the Moon, mostly seen as an excess of impacts on the leading hemisphere (apex) over the trailing hemisphere (antapex), has long been discussed. Recent work [1,2], based on numerical orbital dynamics simulations of candidate impactors, predicts that cratering of the Moon is not uniform, with the cratering rate varying within ~25% in either direction from the global average. These variations are a combination of apex / antapex asymmetry and minor concentration of impacts at low latitudes. In this work we use the particular prediction from [2] (**Fig. 1**) and refer it as LFW. Observational verification of these predictions is important for the validation of crater-based chronology and for understanding of impact processes on the Moon and other planets. This, however, is not easy, because old craters are obliterated and we need a means to obtain a representative time slice within the observed crater population.

The present-day impact distribution has been assessed in [3] with a subset of 56 impacts registered by Apollo seismometers; the observed distribution does not contradict LFW, but the number of impacts is too small to conclusively assess the goodness of fit. Rayed craters are known to be the youngest; recently they have been used in [4] and [5] to assess cratering asymmetry. Although the results do not contradict the predicted apex/antapex asymmetry, it was noted in [5] that the spatial distribution of rayed crater is nonuniform and patchy and not well described by LFW; here we show this in a statistically robust way. We also use a new means to distinguish a subpopulation of the youngest craters, steepness of their walls, and come to a similar conclusion.

Crater wall steepness: We started with the complete catalog of lunar craters with diameter D>20 km [6] and restricted our study to 4593 craters with D<80 km. With an automated procedure we selected all LOLA profiles that cross each crater close enough to its center, identified sections of each profile that correspond to the northern and southern walls of each crater, excluded sections where walls were poorly identifiable (which happened for old craters but almost never for Copernican and Eratosthenian-aged craters), excluded walls that have less than 4 good profiles (35 craters were thus excluded), and identified the steepest point-to-point segment (57 m long) on each wall profile segment. Of all steepest segments at each wall we selected the upper quartile (for example, if there were 10 LOLA profiles crossing a wall, we selected the 3rd steepest of those 10) as a measure of wall steepness; of northern and southern walls we chose the steepest. The procedure described is tolerant to defects in LOLA profiles, minimally affected by the strongly uneven density of LOLA profiles, and gives an objective measure S of crater wall steepness regardless of the complicated morphology of complex craters. The median S over the whole crater population is 27.3º; craters with S > 33º make 9% of the whole population.

All 41 Copernican craters in 20 km < D < 80 km range [7,8] have S > 30º with one outlier (Taruntius, S = 27.5º). All 39 rayed craters from [5] in this size range have S > 33º with the same single exception. Of 82 Eratosthenian craters [7] with sufficient LOLA coverage, 73 have S > 30º, including 46 with S > 33º. There is no systematic difference, however, between steepest Eratosthenian and Copernican craters. Of 32 craters with clear stratigraphic superposition over mare materials [6], 28 have S > 33º, and only 2 have S < 31º (Bullialdus A and Mitchell); both are covered by proximal ejecta of nearby younger larger craters (Bullialdus and Aristoteles, respectively). All these correlations indicate that S can be used to distinguish younger and older craters with some certainty. Here we use S > 33º as a criterion for a young subpopulation of craters. Since the model age of this subpopulation exceeds typical mare ages, some of these craters were obliterated by mare-forming lavas; therefore to assess cratering nonuniformity, we need to exclude the maria. This leaves 361 craters for such an analysis. The particular choice of the 33º threshold is based on the fact at this threshold the spatial distribution changes. For example, the subpopulations 31º < S < 33º and 30º < S < 31º are similar to each other and have a prominent scarcity of craters in the Orientale basin and surroundings, while for chosen S > 33º there is no apparent Orientale signature. Assuming the Neukum production function (NPF) form [9] and the chronology function from [9], the selected craters yield a model age of 3.53 Ga; the corrected chronology function from [2] gives 3.70 Ga. The latter is consistent with the youngest boundary of 3.72 for Orientale age [10]. The actual size-frequency distribution of S > 33º craters is steeper than the NPF, and more detailed analysis is needed.

Analysis technique: We use spherical harmonics expansion of the crater population to compare the actual and predicted distributions. **Figs. 2** and **3** show the distribution of steep-wall craters and rayed craters smoothed down to harmonics of degree $l \leq 2$. We use the Monte-Carlo method (a large number of simulated random crater populations with prescribed rate distribution and the same number of craters as the actual population) to assess the statistical significance of the difference from predictions (see examples in **Fig. 4, 5** for steep-wall craters). Harmonics of degree $l \geq 4$ are dominated by stochastic noise.

Results: For both rayed and steep-wall craters, the apex enhancement (spherical harmonic $C_{1,-1}$) exceeds the confidence limits for a uniform distribution (in **Fig. 4** the big dot is outside the cloud of orange dots). This enhancement is greater than the LFW prediction, but the deflection from LFW is within the confidence limits. For both crater sets, concentration toward the equator ($C_{2,0}$) is stronger than the LFW prediction, but for steep-wall craters it is not significant (in **Fig. 4** the big dot is inside the cloud of black dots). Both data sets show statistically significant deflection from LFW expressed in harmonics that should be zero from symmetry considerations. For steep-wall craters this excessive patchiness is mostly expressed as a significant depletion in the southern farside, roughly coincident with the South Pole-Aitken basin (SPA) (mostly in harmonic $C_{2,-1}$, **Fig. 3**; the big dot is outside the cloud in **Fig. 5**). Rayed craters show similar depletion in the SPA region, but also in the northern high latitudes (Fig. 3). The distribution of rayed craters has a high power in harmonics of $l = 3$.

Discussion: The observed patchiness of the distribution of the youngest craters requires explanation. For rayed craters, possible explanations have been discussed in [5]. Below we overview possible ways to explain the patchiness of steep-wall craters, but none are satisfactory at this point. (1) *Bombardment showers*: a significant proportion of young craters formed in a few events of multiple impacts. This is consistent with the observed higher patchiness of rayed craters (younger population, hence, fewer shower events, hence, stronger patchiness). However, this explanation is difficult to reconcile with the present-day rates of small impacts on the Moon (seismic data), Mars (direct imaging), and the Earth (fireballs), as well as with the present-day population of the near-Earth asteroids. The mechanism of such showers is also illusive. (2) *Regional variations in production of steep walls* seems implausible. The youngest craters on the maria, heavily cratered highlands, and Orientale ejecta, all have consistently steep walls. It is natural to expect the properties of the South Pole-Aitken basin material not to differ drastically from these end-members, and equally steep walls of freshly emplaced craters should be expected there. (3) *Regional variations in degradation of steep walls* seem also problematic. Strong gravitational relaxation of craters within the SPA region (e.g., induced by regional excess of geothermal heating) seems unsupported by the observed crater morphology. Regional enhancement of the regolith gardening rate is consistent with the observed low hectometer-scale topographic roughness in the SPA, but the mechanism of such enhancement is hard to imagine.

References: [1] Gallant J. et al. (2009) *Icarus, 202,* 371–382. [2] Le Feuvre M. and Wieczorek M. (2011) *Icarus, 214,* 1–20. [3] Kawamura T. et al. (2011) *GRL, 38,* L15201. [4] Morota T. and Furumoto M. (2003) *EPSL, 206,* 315–323. [5] Werner S. C. and Medvedev S. (2010) *EPSL, 259,* 147–158. [6] Head J. et al. (2010) *Science, 329,* 1504–1507. [7] Wilhelms, D. (1987) The geologic history of the Moon, USGS Prof. Pap 1348. [8] McEwen A. et al. (1997) *JGR, 102,* 9231–9242. [9] Neukum G. et al. (2001) *Space Sci. Rev., 96,* 55–86. [10] Stöffler D. and Ryder G. (2001) *Space Sci. Rev., 96,* 9–54.

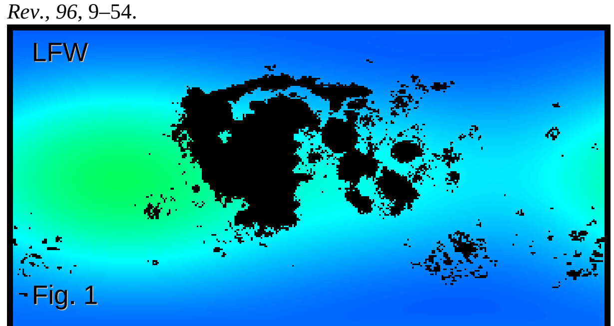

Fig. 1

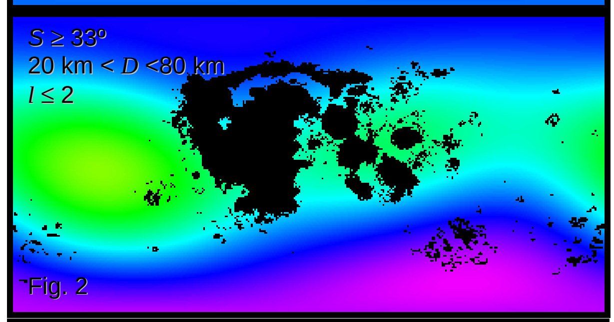

Fig. 2

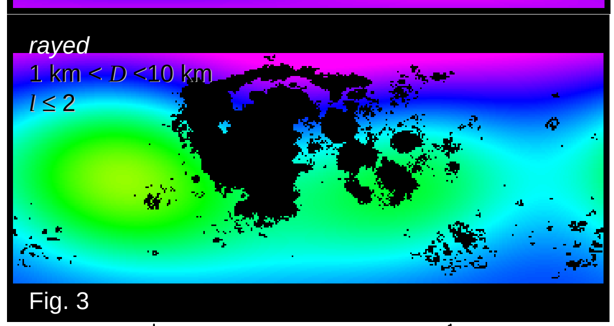

Fig. 3

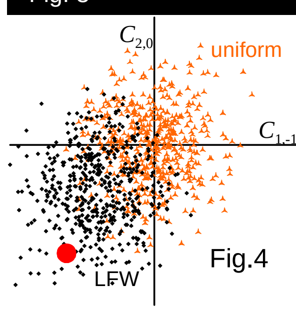

Fig.4

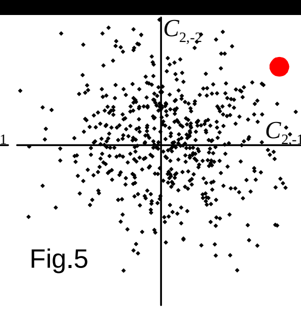

Fig.5