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Comment

Rebuttal to the comment by Malhotra and Strom on ''Constraints on the source of lunar cataclysm impactors''

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ABSTRACT

Ćuk et al. (Ćuk, M. Gladman, B.J., Stewart, S.T. [2010]. Icarus 207 590–594) concluded that the the lunar cataclysm (late heavy bombardment) was recorded in lunar Imbrian era craters, and that their size distribution is different from that of main belt asteroids (which may have been the dominant pre-Imbrian impactors). This result would likely preclude the asteroid belt as the direct source of lunar cataclysm impactors. Malhotra and Strom (Malhotra, R., Strom, R.G. [2011]. Icarus) maintain that the lunar impactor population in the Imbrian era was the same as in Nectarian and pre-Nectarian periods, and this population had a size distribution identical to that of main belt asteroids. In support of this claim, they present an Imbrian size distribution made from two data sets published by Wilhelms et al. (Wilhelms, D.E., Oberbeck, V.R., Aggarwal, H.R. [1978]. Proc. Lunar Sci. Conf. 9, 3735–3762). However, these two data sets cannot be simply combined as they represent areas of different ages and therefore crater densities. Malhotra and Strom (Malhotra, R., Strom, R.G. [2011]. Icarus) differ with the main conclusion of Wilhelms et al. (Wilhelms, D.E., Oberbeck, V.R., Aggarwal, H.R. [1978]. Proc. Lunar Sci. Conf. 9, 3735–3762) that the Nectarian and Imbrian crater size distributions were different. We conclude that the available data indicate that the lunar Imbrian-era impactors had a different size distribution from the older ones, with the Imbrian impactor distribution being significantly richer in small impactors than that of older lunar impactors or current main-belt asteroids.

1. Introduction

Ćuk et al. (2010) concluded that the tail end of the lunar cataclysm at 3.9 Gyr ago (Gya) was produced by impactors that had a size–frequency distribution (SFD) different from that of main belt asteroids. By ''lunar cataclysm impactors'', we mean the population present in near-Earth space at the time of Imbrium and Orientale impacts. The crater density on the Orientale basin is about five times too large to be generated by the subsequent integrated Near-Earth Asteroid (NEA) bombardment, so most post-Orientale (and also post-Imbrium) craters must have also been created by lunar cataclysm impactors. Therefore most craters that formed after the Imbrium impact were produced during the lunar cataclysm.

Ćuk et al. (2010) find that the Imbrian craters have a SFD that is significantly different from one expected if the impactors were main belt asteroids. This conclusion is based on two published lunar crater SFDs that are of Imbrian age: class 1 (morphologically fresh) nearside craters reported by Strom et al. (2005) and stratigraphically identified Imbrian craters studied by Wilhelms et al. (1978). Both of these lunar crater SFDs indicate impactor populations with a steeper SFD (in the 1–5 km impactor diameter range) than that of main belt asteroids; that is, the population has a larger fraction of small impactors than the main-belt asteroids show today. Thus, the bombardment episode that formed the Imbrium and Orientale basins could not have been produced by gravitational destabilization of the main asteroid belt with a present-day SFD.

In a Comment paper, Malhotra and Strom (2011; hereafter MS11) claim that our conclusions cannot be correct for a variety of reasons. Most of their arguments deal with pre-Imbrian lunar highlands, which are stratigraphically older than the Imbrian surfaces that indisputably formed at 3.85 Gya. A number of points in MS11 reiterate their hypothesis that the old lunar highlands (and old terrains on other inner planets) were primarily cratered by main belt asteroids during the belt's dynamical clearing.

Ćuk et al. (2010) do not dispute the possibility that ancient highlands were cratered by asteroids derived from the main belt via size-independent processes. More precisely, is not the *source* (and therefore SFD) of the dominant highland craters that we dispute, but their *absolute age*, which we do not think is the same as

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3.85–3.9 Gyr ages of many Apollo samples. We simply argue that the last wave of impactors at 3.85 Gya (which can be related to Imbrium basin and Apollo samples) were not gravitationally-destabilized main belt asteroids. The exact origin of pre-Imbrium terrains on the Moon (or other planets) is therefore not relevant for our argument. The only point in MS11 directly related to our paper concerns the use of Wilhelms et al. (1978) data and is addressed in the next section.

2. Imbrian crater distribution from Wilhelms et al. (1978)

Malhotra and Strom (2011) combine data from Wilhelms et al. (1978) Tables 2 and 3 to construct a single SFD of Imbrian primary craters for the 8–128 km range. MS11 claim that the resulting curve slopes to the lower left on an R-plot and therefore is not consistent with lunar class 1 craters (MS11, Fig 1). However, this distribution plotted by MS11 contains an important error. Wilhelms et al. (1978) present two different Imbrian crater data sets: one containing only craters below 30 km (the three leftmost points in MS11 Fig. 1, labeled Lunar Imbrian Craters), and the other containing craters above 20 km (all other points on this curve). Wilhelms et al. (1978) divided these two crater populations into two different data sets for a reason: the larger craters have been counted mostly in the highlands and the smaller ones in the subset of the LAC (Lunar Astronautical Chart) area which contains many maria. Naturally, Imbrian craters found in the highlands would be more numerous because the late-Imbrian formation of maria erased earlier craters. The different densities, which are the result of the different ages of the two counting areas, lead to the discontinuity between the number of craters in the 16–22.5 km and 22.5–32 km bins in Fig. 1 of MS11. This discontinuity, which is a major plank of MS11, is not a real signal in the data, but merely the product of combining two incompatible data sets.

Wilhelms et al. (1978) clearly believed these two areas to be of different ages. The Wilhelms et al. (1978) Fig. 6 caption contains the sentence: "Offset in Imbrian curve [at 20 km] presumably is due to the sample <20 km averaging slightly younger than the sample ⩾20 km." Given this statement in the original paper, we do not think it is justified to plot a continuous size-distribution across the break at 20 km. While the two samples in Wilhelms et al. (1978) overlap in 20–30 km range, it is hard constrain relative crater retention ages of these two units using direct crater counts. The ratio of average densities of Imbrian and younger craters in these two samples is 0.84 ± 0.14 (i.e. LAC area has 84% of the larger area's crater density for these classes of craters).

Fig. 1 demonstrates different ways that the LAC and 20+ km distributions might be combined (in the format of the standard R-plot). The histogram-like lines plot the Imbrian and younger (Eratosthenian and Copernican) craters over 20 km in diameter from Wilhelms et al. (1978) Table 2 (red), along with Imbrian and younger primary craters smaller than 30 km from their Table 3 ("LAC area"; green). The bin borders are all multiples of $\sqrt{2}$, increasing from 20 km for the larger crater set, and decreasing from 30 km for the LAC set. A possible combination of these two distributions is indicated by the black line, which is obtained by increasing the LAC density by 35%, to make the R value in the overlap region identical. This is equivalent to assuming that LAC area has 74% of the crater density of their larger-crater counting area. The combination of these two SFDs is now consistent with the SFD of class 1 craters (blue line), while having a slightly higher absolute crater density than class 1 craters. Note that large Poisson uncertainty detailed above allows for a range of calibrations. The black "scaled LAC" distribution we plot in Fig. 1 is not a real data set and should not be used outside this simple demonstration. However, it is clear from the above discussion that both Imbrian crater data sets in Wilhelms et al. (1978) are compatible with having the same SFD as the class 1 craters from Strom et al. (2005).

Since there is no way to securely calibrate the two Wilhelms et al. (1978) data sets, we used only the 20+ km crater counts in Ćuk et al. (2010). Fig. 1 also plots the old highland crater SFD from Strom et al. (2005), which is significantly relatively deficient in smaller craters when compared to Imbrian and younger terrains. We conducted a Kolmogorov–Smirnov test (Press et al., 1992; Stefanick and Jurdy, 1996) on the cumulative distributions of Wilhelms et al. (1978) Imbrian and Nectarian $D > 20$ km crater sets. We find that the probability of these two samples being drawn from the same population is less than 0.1 %. This difference between SFDs on different age terrains is after all the main conclusion of Wilhelms et al. (1978) and is in direct conflict with the claim of MS11.

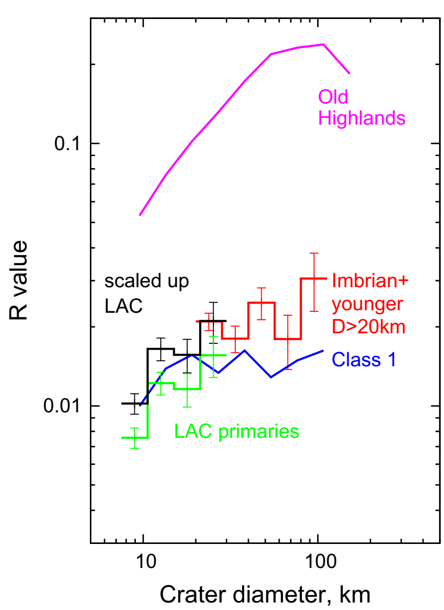

Fig. 1. An R-plot comparing Wilhelms et al. (1978) primary crater size distributions (histogram lines) to the Strom et al. (2005) class-1 (blue curve) and old highland craters (magenta curve). Green line (left-hand side) stands for LAC area Imbrian and younger primaries, and the red line (right) plots 20+ km Imbrian and younger craters. The black histogram line was obtained by scaling up LAC area crater density by 35%, in order to match the 20+ km crater distribution at the overlap. The combined Imbrian and younger SFD (black and red histograms) is very similar in shape to that of class 1 craters, with a slightly higher absolute density. It is clear that these distributions agree with each other as long as the LAC area is somewhat younger than the areas over which 20+ km craters were counted (as already suggested by Wilhelms et al. (1978)).

3. Other issues

In our original paper, we use "logarithmic bin differential" size distribution exponents, which are 1 higher than simple differential ones. The use of logarithmic bins is fairly standard and results in differential size distribution power law exponents that are lower by 1 compared to those calculated using constant size bins. See the Appendix in Durda and Dermott (1997) for a detailed discussion. However, in our original paper, on page 593, we mistakenly omitted the qualifier "log-bin", resulting in an erroneous statement that the differential slope of population 2 craters is close to -2 (when it should be -3). This mistake has no wider implications on our argument, and does not signify any real difference in opinion between our group and MS11.

In their third argument, MS11 state that the class 1 crater SFD is different from the one of post-Orientale craters (as reported by Strom, 1977). This perceived difference is not statistically significant. Using the Kolmogorov–Smirnov test, we find that post-Orientale SFD is consistent with both class 1 and highland crater populations (identity with either cannot be excluded with even 90% confidence). Given that these size distributions are all relatively similar, the approximately 200 craters on the Orientale basin are just not enough to make definitive statements about the post-Orientale size distribution. The absolute crater density for both Orientale and Class 1 craters are the same; this fact leads to the fundamental conclusion that the craters were produced by the same impactors if one accepts that Class 1 highland craters are younger than other highland craters. This density argument is stronger than the less-certain shape of the SFD (because statistical scatter affects the SFD shape more than it does the average R value). In contrast, there is less than 0.1% probability that class 1 and highland craters are drawn from the same population (each of these groups has over 1000 craters). Recently, Head et al. (2010) also reported, on the basis of craters identified through altimetry, that the difference between the Orientale basin and mare crater SFD is not statistically significant. While this is partly due to limited number of craters involved, it is fair to say that no existing data set can exclude the identity between the post-Orientale and class 1 crater SFDs.

In their fourth argument, while acknowledging that Strom et al. (2005) did present class 1 craters as a record of population 2 impactors, MS11 assert that class 1 craters do not reflect a real impactor population, as a morphological class does not guarantee a time-clustered group of craters. Because of the limited surface modification and impactor flux subsequent to the lunar cataclysm, there is no quantitative reason to suspect that class 1 craters differ significantly from post-Orientale craters. Class 1 craters are consistent with all other data we have on Imbrian impactors. Most importantly, the class 1 crater SFD is identical to the Wilhelms et al. (1978) stratigraphically-selected Imbrian craters (with $D > 20$ km), and is also consistent with the (significantly less constrained) post-Orientale crater SFD and number density from Strom (1977) and Head et al. (2010). Unless new data or analyses show that Imbrian craters are different from class 1 craters, we do not think that it is justified to ignore the SFD of class 1 craters when discussing Imbrian period impactors.

4. Summary

We show that the MS11 misrepresent the findings of Wilhelms et al. (1978) by assuming that all areas studied are of the same age. We show that all available lunar crater counts from the Imbrian period (Strom, 1977; Wilhelms et al., 1978, 1987; Strom et al., 2005; Head et al., 2010) are consistent with a size–frequency distribution that has a cumulative (or log-bin differential) exponent close to -2 (for craters with $D > 11$ km). Furthermore, Wilhelms et al. (1978) find that the Imbrian crater SFD is incompatible with the Nectarian one. Therefore, all available data point to a different lunar impactor population at the epoch of formation of Imbrium and Orientale compared to earlier crater populations. The younger crater size distribution, represented by the Wilhelms et al. (1978) Imbrian and Strom et al. (2005) class 1 craters, is the one associated with the lunar cataclysm at 3.85 Gyr ago. The older crater population is consistent with impactors similar to main-belt asteroids and predates the 3.85 Gyr event recorded at Apollo 14-17 landing sites. Further exploration, observations and theoretical work are clearly needed to understand the Moon's cratering history.

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