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Comment

Comment on “Constraints on the source of lunar cataclysm impactors” (Cuk et al., 2010, Icarus 207, 590–594)

Renu Malhotra [*], Robert G. Strom

Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, United States

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ABSTRACT

Cuk et al. (Cuk, M., Gladman, B.J., Stewart, S.T. [2010]. Icarus 207, 590–594) argue that the projectiles bombarding the Moon at the time of the so-called lunar cataclysm could not have been mainbelt asteroids ejected by purely gravitational means, in contradiction with a conclusion that was reached by Strom et al. (Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A. [2005]. Science 309, 1847–1850). We demonstrate that Cuk et al.’s argument is erroneous because, contrary to their arguments, the lunar highlands do register the cataclysm impacts, lunar class 1 craters do not represent the size distribution of the cataclysm craters, and the crater size distributions on the late-forming basins are quite similar to those of the highlands craters, albeit at a lower number density due to the rapid decline of the impact flux during the cataclysm.

Debate over the lunar cratering history has endured over the past four decades, particularly with regard to the “late lunar cataclysm” hypothesis that the Moon suffered a spike in the rate of bombardment at ~3.9 Gyr ago (Tera et al., 1974). The crater record of the Moon has been interpreted in various studies as being either consistent with this hypothesis or consistent with a smooth decline in the bombardment rate albeit especially rapid decline near the ~3.9 Ga epoch (e.g., review by Chapman et al. (2007)). A related issue has been the source of the impactors that were hitting the Moon before, during and after the putative cataclysm event and the dynamical mechanisms that controlled their transport. Indeed, the endurance of the debate over the lunar cataclysm is in large part due to the elusiveness of answers to the questions about the origin of the cataclysm impactors. This topic has received renewed attention recently due to new insights into the dynamical history of the Solar System. The discovery of the Kuiper belt (Jewitt and Luu, 1993) and increasing knowledge of its dynamical structure shows that the Kuiper belt preserves compelling evidence of a rearrangement of the Solar System’s architecture during an epoch of planetesimal-driven giant planet migration sometime after the formation of the planets (Malhotra, 1993, 1995; recent reviews by Chiang et al. (2007) and Gomes (2009)). One of the consequences of giant planet migration may be a late heavy bombardment of the inner planets, including the late lunar cataclysm (Gomes et al., 2005). This linkage between giant planet migration and the late heavy bombardment is by no means firmly established, but it has generated significant discussion and appears worthy of detailed investigation.

Perhaps the most compelling observational evidence for the linkage between giant planet migration and the late heavy bombardment was identified by Strom et al. (2005) in a study of the size distributions of asteroids and of the impact crater size distributions on the terrestrial planets. Their results are summarized as follows. First, they noted that there exist two distinct size–frequency distributions [SFDs] in the crater record: so-called ‘Population 1’ found on the heavily cratered terrains has a crater SFD quite distinct from ‘Population 2’ which is found on lightly cratered terrains; Population 1 is found on the Moon, Mars and Mercury (but not on Venus because that planet has been recently resurfaced), Population 2 is found on all four bodies. Second, they found that the SFD of the observed main asteroid belt is the same as the SFD of Population 1 impactors (the latter inferred by using a standard crater-projectile scaling relationship), whereas the SFD of Population 2 impactors is the same as that of the observed near-Earth asteroids (NEAs). By the basic principles of crater chronology, the high crater density of Population 1 is associated with an ancient epoch whereas Population 2 is associated with a relatively younger epoch. From these correspondences of the two distinct asteroidal SFDs with the two distinct crater SFDs and from their age correlations (Population 1 on older terrains and Population 2 on younger terrains), Strom et al. provided the following interpretation. (1) The mainbelt asteroids (with their current SFD) were the dominant impactors at early times whereas the NEAs are the dominant impactors at younger epochs (including the present); the SFD of the NEAs is different from its source population in the main asteroid belt because size-dependent processes (such as the

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[*] Corresponding author.
E-mail address: renu@lpl.arizona.edu (R. Malhotra).

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Yarkovsky effect) produce a relative overabundance of smaller bodies that drift out of the main asteroid belt to enter the transient NEA population. (2) The SFD of the main asteroid belt has not changed since the epoch when most of the Population 1 impacts occurred. (3) The main asteroid belt must have suffered a gravitational instability that ejected asteroids in a size-independent way to produce most of the Population 1 impacts. Because a gravitational instability in the asteroid belt would lead to a relatively quick injection of asteroids into the inner Solar System, and because the dynamical lifetimes of small bodies in the inner Solar System are relatively short, the implication is that there was a spike in the flux of impactors at some ancient epoch. This constitutes independent evidence and support for the "late heavy bombardment" or "terminal lunar cataclysm" hypothesis of Tera et al. which posits an impact flux spike at ~3.9 byr ago. Additionally, conclusion (2) above regarding the preservation of an ancient size–frequency distribution in the collisionally evolved main asteroid belt is supported by the modeling studies of Bottke et al. (2005) and O'Brien and Greenberg (2005), and conclusions (1) and (2) are both also supported by the extensive cratered surface modeling work of Richardson (2009).

Cuk et al. (2010) argue that the results of Strom et al. are incorrect because the cataclysmic bombardment of the Moon actually had an impactor size distribution that was similar to Population 2, rather than the Population 1 identified by Strom et al. Their argument is as follows. They state that there is "a complete lack of absolute dates for heavily cratered terrains" on the Moon, and therefore the heavily cratered lunar highlands cannot be used to characterize the lunar cataclysm impactors. So, they focus on "Imbrian" craters. (*Imbrian* craters are a stratigraphic age classification defined by Wilhelms et al. (1978) as those craters that are younger than the Imbrium basin but are older than the Eratosthenes mare.) The Orientale basin is the freshest of the large impact basins in the inner solar system and that formed at the tail end of the lunar cataclysm. The impact craters on Orientale record the cataclysm impactors. They claim that there is a similarity of the densities of the lunar class 1 craters[1] and of the Imbrian craters and the Orientale craters, and that these crater populations must have the same age and the same origin. They argue that, because Orientale records the lunar cataclysm impacts, this means that the lunar class I craters also record the cataclysm impactors. (It is emphasized that the connection between the lunar class 1 craters and the lunar cataclysmic bombardment rests not on the SFDs of craters but on their spatial density.) They then examine the SFD of the impactors inferred for the lunar class I craters, which they state[2] has a differential power law index of "-1.9 or -2". This SFD is rather *dissimilar* to the SFD of the current asteroid belt, ergo the cataclysm impactors could not have been mainbelt asteroids with their current SFD. Therefore, they argue, the inference made by Strom et al. that the lunar cataclysm was produced by a gravitational instability in the main asteroid belt is wrong.

If this claim were true, it would render void the link between the late heavy bombardment and a gravitational instability of the main asteroid belt. However, Cuk et al.'s argument and analyses have major flaws that we describe here.

First, Cuk et al.'s basic premise, "a complete lack of absolute dates for heavily cratered terrains", is factually incorrect. There are, in fact, a large number of lunar samples of the heavily cratered lunar highlands that have accurate radiometric measurements (e.g., Stoffler and Ryder, 2001, Tables IV and VI) and measurements of lead isotope systematics (Tera et al., 1974). These data have shown that the lunar crust is ancient, approximately ~4.5 Gyr old (and was not entirely obliterated by the subsequent bombardment), and that the Moon suffered widespread shock metamorphism and a major lead remobilization event near ~3.9 Ga: radiogenic lead that was generated in whole rock during the 4.5–3.8 Ga time interval was mobilized (and re-mixed with non-radiogenic lead) and spread widely near the end of that time interval, specifically 4.0–3.8 Ga. The implication is that the Moon suffered very heavy bombardment near the end of that time interval. It follows that the impact craters on the lunar highlands have been accumulating from at least that epoch of ~3.9 Ga because there is no evidence of widespread resurfacing or volcanism on the lunar highlands since that epoch. Therefore, the inescapable conclusion is that the lunar highlands register the heavy bombardment craters (as well, of course, the cumulative impact history since then). The alternative—that the ~3.9 Ga event is dissociated from the most densely cratered terrain on the Moon—is not supported by the facts.

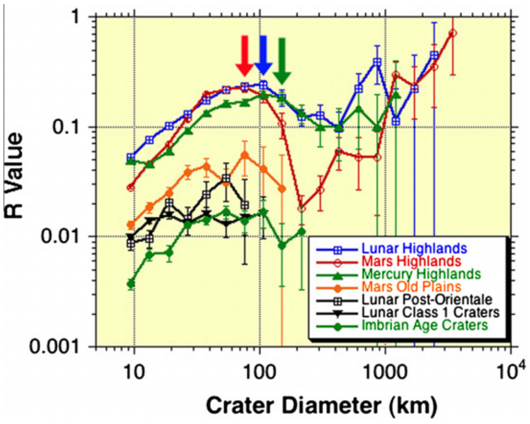

Fig. 1. The three uppermost curves are for the lunar highlands and the Mars and Mercury heavily cratered terrain. This characteristic shape is known as Population 1. At a lower density are crater curves for the older plains of Mars, the post-Orientale lunar craters and the Imbrian lunar craters. Also shown is the lunar class 1 craters curve. The red, blue and green arrows indicate the "downturn crater diameter" for Mars, Moon and Mercury; see text for explanation (lunar highlands and Mars data is as in Strom et al. (2005); Mercury highlands is from MESSENGER data, Strom et al., 2010; lunar class 1 is from Arthur et al. (1963, 1964, 1966); Imbrian lunar data are from Wilhelms et al. (1978), and the post-Orientale is from Strom (1977); the latter has been verified with new counts made by RGS of Lunar Orbiter and Clementine images).

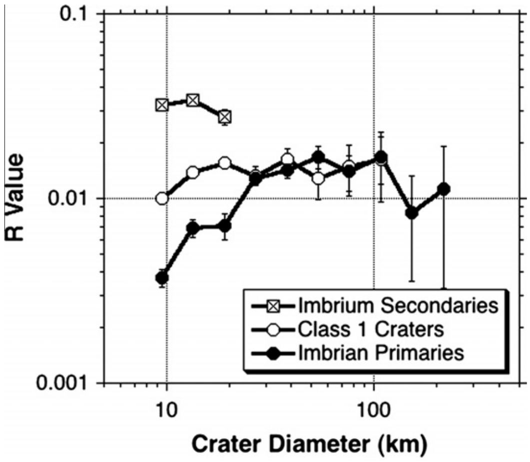

Fig. 2. The *R*-plots of the SFDs of Imbrian primary craters, Imbrian secondary craters and class 1 craters on the Moon.

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[1] Lunar class 1 is a morphology classification for craters that appear the most "fresh"; these are discussed more below.

[2] The power law index of "-1.9 or -2" attributed by Cuk et al. for the differential SFD of the lunar class 1 craters' impactors and of the Population 2 impactors is erroneous. The differential SFD of Population 2 craters has power law index -3.

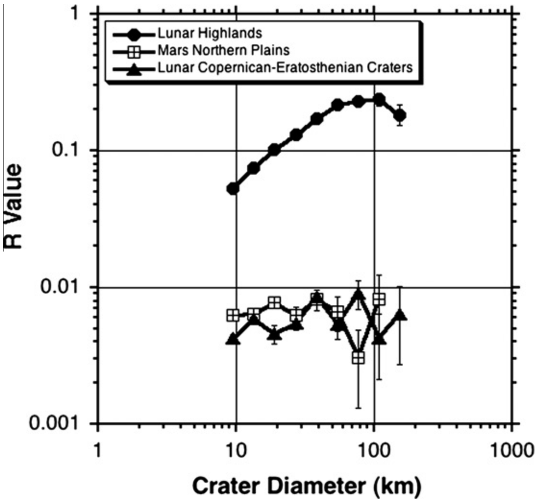

Fig. 3. The lunar Copernican–Eratosthenian craters' SFD compared to the Mars Northern Plains craters (Population 2) and the lunar highlands (Population 1). The Copernican–Eratosthenian is the youngest crater system on the Moon.

Second, while there is little doubt that Orientale records the tail end of the cataclysm impactors, its lower crater density is not by itself indicative of a different impactor source population, contrary to Cuk et al.'s arguments: it stands to reason that the spatial density of craters on Orientale would be expected to be lower than on the heavily cratered lunar highlands, *precisely because it is the tail end of the bombardment that is recorded here*. That the density of craters is almost an order of magnitude lower on Orientale than on the lunar highlands indicates a rapid decline of the impactor flux at ∼3.9 Ga, a conclusion widely accepted in the literature on the crater record (e.g., Chapman et al., 2007).

Third, the SFD of the post-Orientale craters is *not* the same as the class 1 craters. Fig. 1 shows[3] the crater SFDs of the heavily cratered highlands of the Moon, Mars and Mercury, as well as the old martian plains, the post-Orientale craters and Imbrian craters; also shown for reference is the SFD of the lunar class 1 craters (as given by Arthur et al. (1963, 1964, 1966)). It is evident that, while the lunar class 1 is a nearly flat curve in the *R*-plot, the post-Orientale SFD is not flat over the entire range of measured crater diameters.

Furthermore, the SFD of the Imbrian craters is quite dissimilar to the lunar class 1 craters. In Fig. 2, we plot the SFD of the Imbrian primaries and Imbrian secondaries, as well as the class 1 craters. The source of the data for Imbrian craters (both in Cuk et al.'s work as well as here) is Wilhelms et al. (1978). Tables 2 and 3 in the Wilhelms et al. paper provide the number of craters of a given size for several stratigraphic ages of craters and the areas over which they were counted. These data include Imbrian primaries, Imbrian secondaries, and Copernican–Eratosthenian craters; the latter are the youngest lunar craters. It is evident that between about 20 km and 100 km diameter the class 1 craters are the same density as the Imbrian age craters, but it is also evident that when we examine the whole of the Wilhelms et al. data for Imbrian primaries (including diameters less than ∼20 km and greater than ∼100 km), this SFD deviates greatly from class 1 craters and from a power-law function of index −3. This is in contrast with Cuk et al.'s description of the Imbrian craters 'appearing unsurprisingly as a "scaled up" version of the class 1 curve'. Our Fig. 2 differs from Cuk et al.'s Fig. 2 in that (i) Cuk et al. did not plot the Imbrian data for crater diameters less than 23 km nor for craters larger than 100 km, and (ii) in the 23–100 km size range, Cuk et al. plotted the "Imbrian and younger" SFD (the combined Imbrian and post-Imbrian craters) rather than simply the Imbrian SFD, as we did.

Fourth, it is important to recognize that the lunar class I craters are a morphologically defined population, not a chronologically or stratigraphically defined one; these craters are found everywhere on the Moon. Morphologically, these are the "freshest", least-degraded lunar craters. The reasons for their fresh appearance are in part their relatively young age and in part their specific locale. Because these are not a stratigraphically-defined population, the SFD of lunar class 1 craters is not a good surrogate for Population 2 on the Moon. Strom et al. (2005) erroneously presented lunar class 1 as representing Population 2 craters on the Moon. The best representation[4] of Population 2 on the Moon is the Copernican–Eratosthenian craters mapped by Wilhelms et al. These are the youngest craters that formed subsequent to all known mare materials (Copernican) or subsequent to all but the youngest mare materials (Eratosthenian). Fig. 3 plots the SFDs of these craters as listed in the Wilhelms et al. Tables 2 and 3; for comparison, we also plot the crater SFD of the Northern Plains on Mars. The Mars Northern Plains are a useful comparison here because they are a stratigraphically defined dataset, their low crater density indicates a young surface, and they cover a large area and therefore provide large numbers of craters with good statistics (Strom et al., 1992). Both curves are very similar to a differential −3 power law size distribution (a flat curve on an *R*-plot).

Fifth, the authors have completely ignored the crater records of the other terrestrial planets, Mercury, Venus, and Mars. For example, Mars has terrains that have been resurfaced at a variety of epochs as evidenced by crater counts, and it best shows the variations in the cratering record. The SFDs on the varied martian terrains clearly show a progression from a shape like that of Population 1 to a shape like that of Population 2 as we go from high crater density terrains to low crater density terrains (see Strom et al., 2005). That the heavy bombardment was common to at least all the terrestrial planets is supported by both the similarity of the magnitudes of crater densities as well as the similarity of the SFDs of craters found on the highlands of the Moon and Mars and Mercury. Because the lunar highlands are clearly associated with the cataclysm (see the first point above), Occam's razor indicates that the Mars and Mercury highlands also record the cataclysm impactors. Their SFDs are irreconcilable with the SFD of Population 2.

One may argue, as Cuk et al. do, that there is no *a priori* reason that two small body populations of independent origin cannot have similar size distributions.

Cuk et al. invoked this point to argue that LHB impactors could have the same SFD as Population 2 impactors while being distinct from the NEAs. One could similarly hypothesize that the Population 1 impactors could be distinct from the main asteroid belt, but just coincidentally share a size distribution function. Because small body populations in the inner Solar System have relatively short dynamical lifetimes, it is not inconceivable that some ancient population that has no current observable remnant might have been the source of the LHB impactors. However, given our current state of knowledge, this is not an economical hypothesis, as it appeals to a presently unknown or unrecognized impactor population, whereas we already have knowledge of an identified source

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[3] In Figs. 1–3, we plot all size distributions using the "Relative" plot method which was devised to better show the size distribution of craters and crater number densities for determining relative ages of planetary surfaces (Crater Analysis Techniques Working Group, 1979). Such a plot shows the deviation of the SFD from a simple power law SFD of index −3. The discretized equation for R is, $R(D) = D^3\Delta N/A\Delta D$; here ΔN is the number of craters with diameter between D_1 and D_2 counted in a surface terrain of area A, $D = (D_1D_2)^{1/2}$ is the geometric mean diameter of the size-bin $\Delta D = D_2 - D_1$. We adopt $D_2 = \sqrt{2}D_1$, in common with much of the cratering studies literature.

[4] Even better statistical representation of the younger Population 2 craters is provided by the large areas of young terrains on Mars, as discussed in Strom et al. (2005).

that is consistent with the observations. But the hypothesis is not easy to falsify, because it posits an unobservable small body source.

Interestingly, there is additional evidence in the crater record, previously published by Strom and Neukum (1988), supporting the economical hypothesis that the main asteroid belt was the source of the LHB impactors. This evidence lies in a comparison of the crater SFDs of the highlands of Mars, Moon and Mercury at the larger diameters where the curves have a downturn to steeper slopes (more negative power law index). The downturn in the Mercury crater curve occurs at a larger diameter size-bin than on the Moon, whereas on Mars, the downturn occurs at a smaller diameter size-bin, as indicated by the red, blue, and green arrows in Fig. 1: on Mars, the downturn starts at about the 76 km size-bin; on the Moon the downturn starts at about the 107 km size-bin, and on Mercury at about the 152 km size-bin. This systematic shift from Mars to Moon to Mercury of the "downturn diameter" of large craters is consistent with an origin of impactors from the main asteroid belt, because the impact velocities of these asteroids are higher on Mercury and lower on Mars, compared to the Moon. Using the Pi-group scaling relationships (Holsapple, 1993) and adopting the median impact velocity of mainbelt asteroids for each planet (38.1 km/s, 18.9 km/s and 12.4 km/s for Mercury, Earth–Moon, and Mars, respectively, Minton and Malhotra, 2010), we find that the diameters of the impactors corresponding to the "downturn diameter" of large craters are very similar: 4.9 km for Mercury, 4.7 km for the Moon, and 4.4 km for Mars. In other words, for the same impactor size, the impact velocity differences produce a shift in the crater sizes that are consistent with the observed shifts in the crater SFDs. The size-bin shifts of the downturn diameter of large craters are therefore consistent with the hypothesis that the objects responsible for the late heavy bombardment originated from the main asteroid belt. This shift and its implication for the orbits of the impacting objects was first noticed by Strom and Neukum (1988), although they did not recognize its significance and connection with the late heavy bombardment.

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