Reply comment on: "Supportive comment on: "Morphology and population of binary asteroid impact craters", by K. Miljković, G. S. Collins, S. Mannick and P. A. Bland - An updated assessment"

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Abstract

In Miljković et al. (2013) we resolved the apparent contradiction that while 15% of the Near Earth Asteroid (impactor) population are binaries, only 2-4% of craters formed on Earth and Mars (target planet) are doublet craters. Using 3D hydrocode simulations to explore the physics of binary impacts, we showed that only 2% of binary asteroid impacts produced well-separated doublets, while the rest covered morphologies ranging from overlapping to elliptical or even circular. We then generated a complete classification dataset to aid in the identification of the (sometimes subtle) morphological characteristics consistent with a binary asteroid impact. We thank Schmieder et al. (2013) for providing additional detailed geochronological constraints which indicate that our lower bound of 2% doublet craters on Earth may in fact be $\leq$1.5%.

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In the section of our paper where we estimate the number of doublet craters on Earth, we drew on literature collected at the Earth Impact Database (EID, Spray and Elliot, 2010). Schmieder et al. (2013) “…warn against the indiscriminate usage of impact ages compiled in this database …”. But the EID is a valuable resource for scientists from a range of disciplines. The Planetary and Space Science Centre that hosts the database welcomes contributions from researchers to keep it up-to-date. We encourage Schmieder et al. to approach the EID Data Manager with some of the specific details included in their comment.

We generally agree with the detailed comments of Schmieder et al. (2013), however there are a number of points of departure, or areas that should be clarified:

With respect to Sierra da Cangalha and Riachao Ring, and Crawford and Flaxman pairs, we noted the same uncertainties, and referenced the same literature, as Schmieder et al. (2013). This is why we assigned these craters a designation as ‘possible’ doublets (Table 1, Miljković et al., 2013), and excluded them when estimating a lower bound for the number of terrestrial doublets.

With respect to Ries and Steinheim, and the difficulties in determining a precise age for Steinheim, Schmieder et al. (2013) note that “Until such issues are resolved, it is unsafe to treat these craters as a ‘proven’ doublet based on their proximity alone”. That is correct, and that is why we did not refer to them as ‘proven’ doublets. Schmieder et al. (2013) return to the idea that only ‘proven’ craters, or ‘proven’ doublets should be part of any study, a number of times. We do not use the word ‘proven’ anywhere in the text: without direct observation, it is impossible to prove that two craters were formed by binary impact. Moreover, scientific theories are never proven: interpretation is based on a balance of probabilities.

With respect to geochemistry, it is true that we did not consider this as a variable in evaluating the EID literature. Although it would have negligible impact (in terms of numbers of doublets) on the apparent contradiction that prompted our study, we note that the presence or absence of an impactor signature (e.g. enrichment in siderophiles) in melt cannot be used as a discriminant in determining whether craters are doublets. 93% of meteorite falls carry an enrichment in siderophiles relative to crustal rocks, but the fraction of analysed impact melts from terrestrial craters that show evidence of a siderophile enrichment is much less (about 40 of the approximately 175 currently known impact structures show evidence of siderophile element enrichment, Koeberl, 2007; French and Koeberl, 2010). The absence of a meteoritic signature at many impact structures may be explained by erosion, but in the numerous cases where impact melts are preserved a plausible explanation is that impactor material was not well mixed, or homogeneously distributed, in melts at these craters - although the craters were generated by chondritic impactors, the geochemical signature of those impactors has not yet been found. The fact that impactor-derived siderophiles have not been found at a specific crater does not necessarily mean that the impactor was a stony meteorite from a differentiated parent body (ie. meteorites with no siderophile enrichment).

Once again regarding uncertainties, terminology, and statistics, in our discussion of Sierra da Cangalha and Riachao Ring we argued that their close proximity warranted their inclusion in our analysis as a ‘possible’ doublet, despite the large uncertainty in their respective ages. The same logic provides even stronger justification for the inclusion of the Clearwater craters, which have a smaller separation, until such time as definitive dating excludes binary impact as a probable cause. Schmieder et al. (2013) quoted our argument and noted that “…‘false doublets’ can occur by a freak of nature”. We do not understand why these statements are contradictory. It is a truism that statistically unlikely events - ‘freaks of nature’ - occur all the time. But in evaluating any process or event it is necessary to constrain probabilities. In this case, the balance of probability is between the likelihood of a widely-separated binary impact and the coincidence of two impacts, close together in space, but separated in time within a period given by the overlap interval of the crater age uncertainties. Unfortunately, neither of these probabilities can be accurately determined at present: the former is poorly constrained by the current statistics of binary asteroids (Pravec et al., 2006; Walsh, 2009); the latter requires knowledge of the impactor flux, the size frequency distribution at 1 AU and the completeness of Earth’s cratering record over the relevant time interval.

However, we can derive a very approximate estimate of the probability of a 'false doublet'—two similar sized craters forming within about two crater diameters of each other—somewhere on Earth, during a time interval ΔT. Assuming a uniform and isotropic flux rate of $\sim 5.6\times 10^{-9}$ craters with diameter $D > 20$ km, per square km, per million years (Grieve and Shoemaker, 1994), and an idealised cumulative crater size frequency distribution (SFD) with a slope of -2 (Melosh, 1989), the number of craters with diameter greater than D that form in an area A (km^2) and during the time interval ΔT (Myrs) is given by:

$$N_{cum}(> D) \approx 5.6 \times 10^{-9} \left(\frac{D}{20}\right)^{-2} \Delta T A \tag{1}$$

The number of false doublets that occur during the time interval ΔT can be estimated by defining A as the cumulative area within a distance of two crater diameters from the center of each and every crater with a diameter between D and $\sqrt{2}D$ that forms during the same time interval over the entire Earth. Neglecting possible overlap, A can be approximated by the number of craters in this size range times the geometric mean area within two crater diameters for this size interval, which is given by:

$$A \approx 4\pi D^2\sqrt{2}\left[N_{cum}(> D) - N_{cum}(> D\sqrt{2})\right] = \frac{4\pi D^2}{\sqrt{2}} N_{cum}(> D) \approx 1{\times}10^4 \Delta T \tag{2}$$

Equations (1) and (2) suggest that during a time interval of 200 Myrs, approximately 50 false doublets should occur (across Earth's entire surface) for craters $\sim$4 km in diameter; three false doublets should occur among craters $\sim$16 km in diameter; and only one false doublet should occur among craters $\sim$32 km in diameter. Given Earth's poor crater retention, the number of preserved false doublets will be much less. Hence, while the $\sim$4 km diameter Suvasvesi false doublet that Schmieder et al. (2013) discuss is expected; false doublets among larger craters, such as the Clearwater craters, are not. Moreover, dividing (1) and (2) by the cumulative number of craters with diameter larger than D for the entire Earth ($A \approx 5 \times 10^8$) gives an estimate of the fraction f of false doublets among the total population of craters:

$$f \approx 2 \times 10^{-5} \Delta T \tag{3}$$

which is independent of D by virtue of the -2 slope of the idealised crater SFD. According to (3), even after a time interval of 200 Myrs the expected percentage of false doublets among an idealised crater population is several times lower than the expected percentage of doublets formed by binary impact ($\sim$2%, Miljković et al., 2013). For closely-separated craters with age uncertainties that overlap by less than $\sim$200 Myrs, binary impact is a more probable cause than separate impacts.

Having considered the comments of Schmieder et al. (2013), including the important addition of Lockne/Målingen as a likely binary asteroid impact (Alwmark et al., 2013), a revised estimate of the number of terrestrial doublet crater pairs is 2-6 out of 132, or 1.5-4.5%, which is still in good agreement with our model prediction of 2-3% (Miljković et al., 2013).

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