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# The Missing Mantle Paradox, and the Statistical Argument for Repeated Hit and Run Collisions

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## Abstract

Mercury's formation can be explained by a giant impact. However, a direct hit blasting off the mantle [1] leaves debris stranded in orbit about the Sun, to be re-accumulated back onto Mercury. A hit and run collision [2] provides a cleaner solution, and in most cases, much lower levels of shock and potentially greater retention of volatiles. However, hit and run is usually followed by subsequent re-collision, and ultimate accretion; an embryo's survival after being a hit and run projectile is unlikely in any single instance. Most of the original planetary embryos have been accreted by Earth and Venus; unaccreted planets are lucky. Here we show that the surviving terrestrial planet population is likely to have about as many hit and run survivors, as it is to have untouched survivors. That is, the differences between Mercury and Mars can be explained in a statistical manner as a consequence of accretionary attrition. We consider applications to asteroids, meteorites and exoplanets.

## 1. Mercury and Mars

Earth, Venus, Mars and some of the largest asteroids have massive silicate mantles surrounding iron cores, and chondritic compositions. Against this backdrop are anomalies like the iron planet Mercury, and the Moon with almost no core, and metallic asteroids like Psyche. The Moon can be explained by giant impact, but for Mercury a giant impact [1] is problematic. Mercury must retain substantial volatiles after its obliteration [e.g. 3] and must somehow avoid accreting its ejected silicates [4].

Impact hydrocode simulations using smooth particle hydrodynamics (SPH) have shown [2] that a proto-Mercury about 3 times its present mass can be stripped of its mantle in one energetic hit and run collision [5] with a larger planet, proto-Venus or proto-Earth. To preserve volatiles we also consider the scenario of multiple hit-and-runs in succession, with each event occurring at relatively low impact velocity (~10 km/s) in a glancing blow. If this sounds like an exotic recipe for making an iron planet, it is. But the point is that the non-exotic recipe is the one that makes Earth and Venus – that is, the one that gathers everything up. The stuff that is left behind, is what concerns us when considering Mercury and Mars, planets an order of magnitude less massive than the others. They are all exotic, and we apply a simple statistical argument to address this concept.

We show that small relics (Mercury, Psyche) can be survivors of repeated hit and run collisions, as witnessed in recent dynamical trials [6]. Specifically, the statistics of attrition makes one mantle-stripped planet (Mercury) probable, alongside one relatively undisrupted planet (Mars), if ~20 comparable progenitors were accreted by Venus and Earth. This is illustrated in Figure 1.

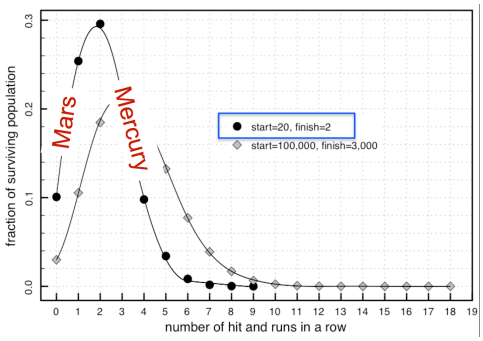


**Figure 1.** Starting from 20 initial embryos, the likelihood of having suffered *h* hit and run collisions in a row increases with the degree of attrition. So for the case of 20 embryos accreting until there are 2 unaccreted original bodies, about half the time you get a Mars-like planet (one or zero hit and runs), and about half the time you get a Mercury-like planet (several hit and runs).

## 2. Vesta and Psyche

For iron asteroids the 'missing mantle paradox' also looms prominent. And how do we strip away so much mantle rock, in some cases [7, 8] down to a bare iron core, while leaving asteroids like Vesta presumably intact? [9] The problem here is quite analogous to Mercury, whose target (proto-Venus or proto-Earth) is the hiding ground for its lost mantle. According to the hit and run hypothesis, the sink for all this missing silicate is the larger accreted bodies at the top of the feeding chain.

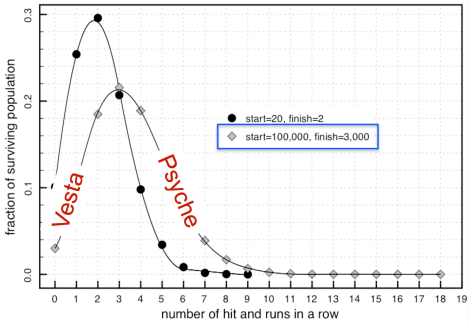


**Figure 2.** Same as Figure 1, but for 100,000 planetesimals accreting onto larger bodies, until 3,000 are left. In this case attrition is stronger, and the survivors are more exotic. About half the unaccreted population has 0-3 hit and runs, and the half of the population has 3-7 hit and runs. In reality collisional accretion and non-accretion is a very messy thing, and the *h*-number simply represents the characteristic number of non-accretionary collisions suffered by the unaccreted remnant bodies.

## 3. Discussion

The missing mantle paradox is only relevant to those few pairwise encounters that do not accrete both bodies. It is not a paradox, because the mantle is in plain view, accreted onto larger planets. Small planets are lucky unaccreted survivors, and the resulting attrition bias is manifested as compositional diversity and a preponderance of iron relics.

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