

**MERCURY, THE IMPACTOR.**

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**Introduction:** The late stages of planet formation in regions closer to the Sun, were characterized by vigorous dynamical interactions [e.g., 1-3]. This environment was conducive to giant impacts among planetary embryos. The most probable scenario for such events are “hit and run” similar-sized collisions (SSCs), in which the system is characterized by small mass ratios and off-axis oblique impacts [4]. Planetary-scale impact events lead to diverse outcomes, which include merging, grazing, partial accretion or erosion and catastrophic disruption, and depend on the specific impact parameters of each event [5, 6].

Mercury, the smallest and innermost planet, is also the most peculiar, in terms of its internal structure and composition [7]. The planet’s bulk properties are a comparatively large iron core, which comprises most of its volume and mass [8]. This is far from a closely chondritic configuration of the other terrestrial planets, which are also much more volatile-rich, and is difficult to reconcile with the common planetary accretion scenarios. The origin of these characteristics is still an open question. There are however several main ideas as to Mercury’s metal/silicate enrichment: Condensation variation in the inner nebula [e.g., 9]; Dynamical separation of metal and silicate planetesimals [10]; and Collisions, which include both major ejecta removal by giant impacts [4, 11] and cratering erosion by multiple small impactors [12].

Removal of most of the silicate-rich mantle from a proto-Mercury could have occurred through a catastrophic disruption collision of a smaller body onto the Mercury target [11] or via a grazing (“hit-and-run”) impact, where proto-Mercury was the projectile that suffered most of the deformation and disruption [4]. Mercury then formed by re-accretion of the disrupted fragments (mostly iron-rich), which did not escape.

The subsequent re-accumulation of ejected fragments can only be efficient if the proto-Mercury silicate mantle was blasted and remained in small enough particles so that radiation drag removes it from the surrounding, before the Mercurian ejecta re-accretes onto the planet (~1-2 Myr) [13]. The ejected fragments that get re-accreted are devolatilized (the energetics of such collision events is enough to vaporize the ejecta and melt/vaporize some portions of the planetary embryo), as such they would also tend lower the core mass fraction. Thus, dynamical separation of ejected material (dynamical interaction

with the environment) [14], or a lower remnant projectile mass and rock-to-iron ratio (permitting subsequent partial accretion events, either of more silicate debris or by merging impacts) are required to explain Mercury’s curious origin via a giant impact mechanism. This is more easily enabled by having proto-Mercury play the part of the significantly deformed and disrupted projectile in a hit-and-run.

**Modeling Issues:** We performed a set of simulations of SSC events, covering a range of mass ratios (1-0.2), impact parameters (0.25-0.96, for near head-on to barely grazing) and impact velocities (~1.5-5 times the mutual escape velocity, as dependent on the mass ratio). We used the smoothed particle hydrodynamics (SPH) code GADGET 2 [15], which was modified to handle tabulated equations of state, such as ANEOS parameters used for SiO<sub>2</sub> and iron), and has been used previously in simulating giant planetary impacts [16, 17]. The initial proto-Mercury mass (as the projectile was set as ~2.25 times its current mass, which is the minimum mass needed to comply with a roughly chondritic composition abundance (70:30 silicate-to-iron ratio). All bodies were allowed to settle to negligible particle velocities in isolation, within ~20 simulated hrs. The total number of particles involved in each of our collision simulations was between 100-300 thousand. All runs were followed for over 24 hrs of simulated post-impact time.

**Results:** Fig. 1 shows the final mass fraction of the projectile remnant (2<sup>nd</sup> largest remnant in the system), as a function of specific impact energy. We normalize this energy to a disruption threshold criteria, which follows the recipe introduced in Leinhardt and Stewart 2012 [5] for the largest remnant mass scaling. However we tweaked the expression for this criteria and used a preliminary version derived from some of our empirical fits to the projectile disruption outcomes from our data.

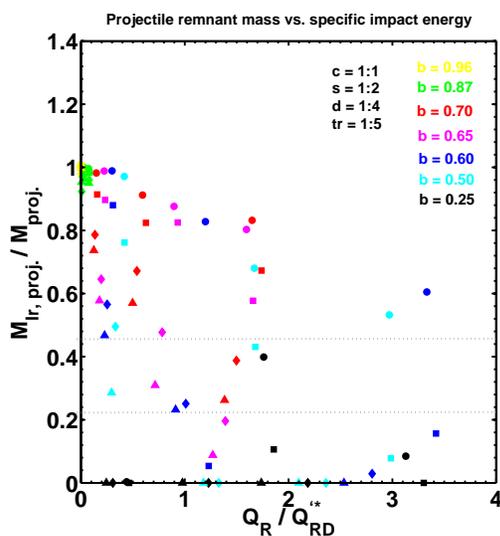
Fig. 2 shows the remnant of the projectile that emerges from a hit-and-run event. An acceptable post-impact Mercury proxy must satisfy the constraints of both mass (~0.5-1 Mercury mass) and density (rock/iron ~0.35-0.65). This leaves 3 distinct cases, all with massive targets and impact parameters characteristic of hit-and-run events. We note, however, that there are more cases, which can be very good candidates for producing Mercury via multiple grazing

and erosion events. These should be characterized by 1-1.5 Mercury masses and rock/iron ratios of ~1-1.5.

Fig. 3 shows a snapshot sequence from the evolution of the collision event for a successful Mercury proxy. We focus on the environment of the projectile (a few Mercury radii across), as it emerges from the event. The projectile seems to be almost disrupted early on, with its silicate mantle severely eroded. However, it re-accretes most of its iron within a few hours, as well as some of the silicate mantle. There is some minor (up to a few %) mixing of the silicate material, between the disrupted mantles of the projectile and the target.

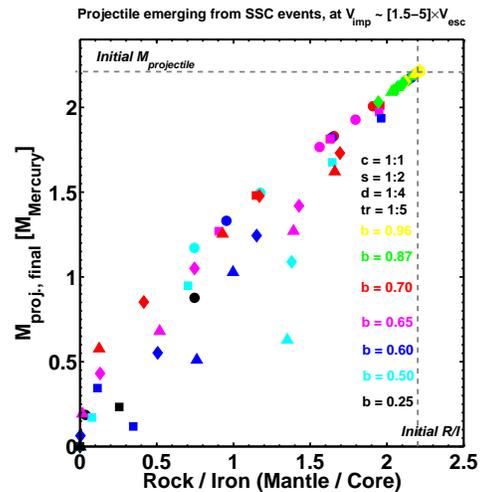
**Acknowledgements:** This work was supported by NASA Origins grant #NNX11AK93G.

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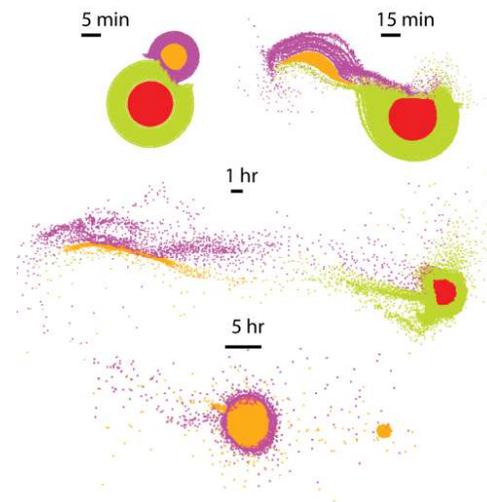


**Figure 1:** Final mass fraction of the projectile remnant (2<sup>nd</sup> largest remnant in the system), as a

function of the normalized specific impact energy. Data points represent our simulation set, for various projectile-to-target mass ratios (symbols), impact parameters (colors) and impact velocities (~1.5-5 times the mutual escape velocity). Gray dashed lines bracket the acceptable mass range for a post-impact Mercury proxy (~0.5-1 Mercury mass).



**Figure 2:** Final mass of proto-Mercury projectile vs. the final composition, in terms of mantle-to-core material ratio. Data points represent our simulation set, with similar notations as Figure 1. Gray dashed lines represent the initial projectile mass (horizontal) and initial projectile rock/iron composition (vertical).



**Figure 3:** Snapshot sequence of the hit-and-run collision event in one of the successful Mercury proxy simulations (0.2 mass ratio, 0.65 impact parameter and  $V_{imp} \sim 3V_{esc}$ ). Shown are times  $t = 0.12, 0.25, 1,$  and  $5$  hours after impact, when the remnant projectile is settled and surrounded by a few silicate debris. The spatial scale bar is  $\sim 2500$  km.