EPSC Abstracts
Vol. 13, EPSC-DPS2019-1349-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Mercury as a stranded runner of Earth-Venus formation

E. Asphaug (1), S. Cambioni (1), A. Emsenhuber (1), R. Furfaro (2), T.S.J. Gabriel (3), S.R. Schwartz (1)
(1) University of Arizona, Lunar and Planetary Laboratory, Tucson, Arizona, United States; (2) Systems and Industrial Engineering, University of Arizona, Tucson, AZ, USA; (3) School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA (asphaug@lpl.arizona.edu)

Introduction

Mercury has revealed itself to be full of geologic mysteries, as reviewed in *Mercury: The View after Messenger* [1]. One of the greatest surprises, to be studied further by the ESA/JAXA BepiColumbo mission and by future landers, has been the preponderance of volatiles and semi-volatiles on the surface. These should have been reduced to less-than-lunar abundances in the remnant planet, according to the classic giant impact model [2] where proto-Mercury is intensely disrupted and dispersed to result in the planet's missing silicate mantle, and a bulk composition which is mostly metallic iron.

One possible idea for the preservation of Mercury's volatiles is a lower velocity giant impact, in which Mercury is the "runner" from a hit and run collision (HRC). Instead of blasting proto-Mercury apart, an HRC pulls the mantle off, by creating outward gravity gradients during a collision into proto-Earth or proto-Venus. Although feasible dynamically [3] it has been found [4] that a single HRC, to get rid of enough mantle, would have to be intensely energetic. In the "best case" single-HRC scenario [3], proto-Mercury impacts a Venus-mass target at $3.25 v_{\rm esc}$ and loses over 3/4 of its mass—a catastrophic event that does leave a metallic runner, as desired, but involves a dynamically exotic projectile [5], in a scenario that might not end up explaining the volatile geochemistry either.

Because of planetesimal damping, most late stage collisions were much slower than this, with impact velocities in the range of around $1.1 - 1.4 v_{\rm esc}$. These velocities are too slow for target disruption, but they result in hit and run collisions as often as accretion; HRC may even be the dominant outcome [6]. Two or three HRCs at those lower velocities could remove as much mantle from a runner as a single, less likely, considerably more energetic event. If the work of mantle removal is divided between 3 HRCs, each at a fraction of the velocity, then far less kinetic energy ends up being converted into heat.

We base our analyses on hundreds of simulations of giant impacts [6], but we have not yet explicitly modeled sequential hit and run collisions, in the sense of using the outputs of one simulation as inputs to another. Although in principle it is not that difficult to do so, it requires making an arbitrary choice for the angle of the second collision, which we have found [7] is indistinguishable from the random distribution. The median collision contact angle is 45° (assuming spheres) and the median angle between the collision plane and the target equator is 90°—except for the few return collisions that happen directly within thousands of years. Prograde collisions followed by prograde collisions would have substantially different outcomes than orthogonal or retrograde collisions, for example, leading to divergent predictions in terms of forward models.

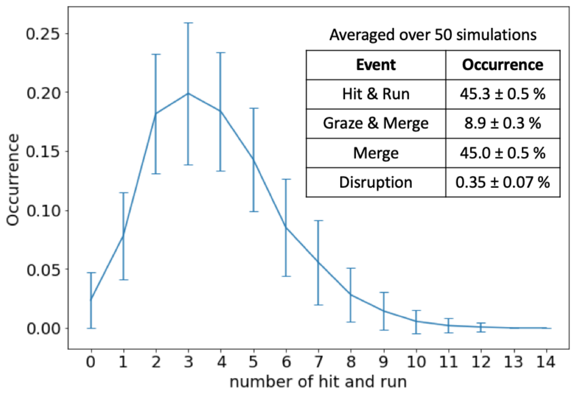
What is meant by "survivor" can mean many things, depending on the kind of hit and run collision (or collisions) that occurred. Apart from any mantle stripping, HRCs have a tendency to decompress the runner's interior, tidally unloading the hydrostatic pressure throughout the body for a timescale of almost an hour, with interesting petrological consequences.

Accreted bodies tell no tales

For now we have taken a closer look at the probability of leaving a multiple hit-and-run remnant "on the table", by which we mean Mercury [4]. We have applied a machine-learning basis for collision outcomes [7] using a Markov-Chain Monte-Carlo analysis. Consistent with our previous estimates, we find that stranded runners are probable, and specifically, that it is likely for Mercury to have been a multiple-HRC survivor.

Detailed simulations of giant impacts have conclusively shown that net accretion only happens about half the time. Just as often, a largely-intact "runner" escapes, or a few, plus a lot of debris. Most of these runners return but some of them remain stranded, at least for the timeframe of 20 Ma that we have studied [7].

When fragmentation and realistic impact conditions are statistically combined (Figure 1), the surviving projectiles tell stories of multiple encounters with their oligarchs, namely proto-Earth and proto-Venus for the



Event	Occurrence
Hit & Run	45.3 ± 0.5 %
Graze & Merge	8.9 ± 0.3 %
Merge	45.0 ± 0.5 %
Disruption	0.35 ± 0.07 %

Figure 1: Occurrence of hit-and-run collisions for test particles that survive simulated terrestrial planetary formation. The distribution results from a "flip-the-coin" statistical study [4] which uses data-driven collision model [7]. Two oligarchs, Earth and Venus, starts at 1/10 of their masses and accrete smaller embryos with initial mass = 0.01 $M_\oplus$. The impact velocity and angle are randomly sampled from a Rayleigh distribution peaking at 1.2 Vesc and $\sin 2\theta$ distribution, respectively. The simulation ends when Earth and Venus achieve their actual masses.

inner solar system. While accretion of *most* of the projectiles is still a necessary outcome of planetary formation, the effect of multiple HRCs is to lengthen the time scale of late stage accretion, and to increase the diversity of the survivors.

Towards an inversion of outcome

The “Mercury problem" is degenerate so far, because different models ([2–4]) produces similar outcomes: a Mercury mass of $0.05M_\oplus$ and core-to-mantle ratio of 0.68. However, while these bulk outcomes may be alike, the collision scenarios are profoundly different in terms of what thermal physics dictates for preservation of volatiles in the thin mantle of the remnant, and the resulting geochemistry of the surface, and beneath the surface, once the planet solidifies.

Data-driven models are quick and accurate. Using data from MESSENGER (volatile abundances, crustal evolution models) a combination of machine learning and Bayesian (Markov-Chain Monte Carlo) statistics applied to giant impact outcomes has the potential to constrain the likelihood of specified scenarios for Mercury and other collisional remnants, through an inversion of outcome (e.g., Figure 2.)

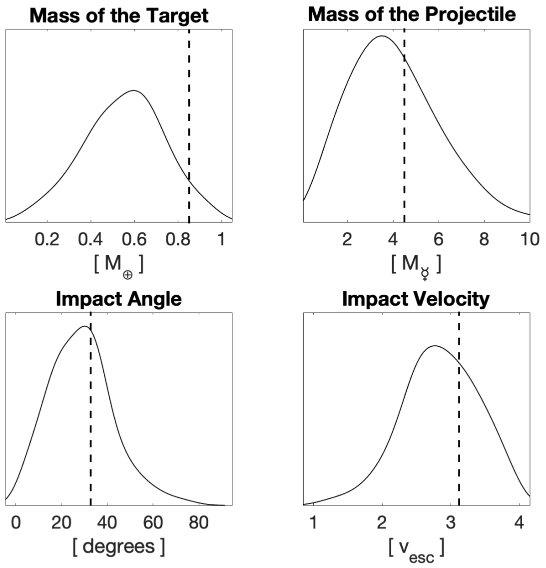


Figure 2: Markov-Chain Monte Carlo Bayesian inversion of the observed geophysical properties of Mercury using data-driven models [6]. The inversion scheme assumes that Mercury is the second largest remnant of a single HRC [3]. The four panels show the normalized posterior distributions for the impact properties; the solution by [3] ($M_{tar} = 0.85M_\oplus$, $M_{proj} = 4.52M_{☿}$, $V_{imp} = 3.25V_{esc}$, $\theta_{imp} = 34^\circ$, dashed lines) is within the admissible values. The predicted collision gives a Mercury-like second-largest remnant with mass $0.05M_\oplus$ and core-to-mantle ratio of 0.67.

References

[1] Solomon, S.C., Nittler, L.R. & Anderson, B.J., *Mercury: The View after Messenger*, Cambridge University Press, 2018. [2] Benz, W., Slattery, W. & Cameron, A. “Collisional stripping of Mercury’s mantle”, *Icarus* 74, 1988. [3] Chau, A., Reinhardt, C., Helled, R., & Stadel, J. “Forming Mercury by giant impacts”, *Ap.J.* 865, 2019. [4] Asphaug, E. & Reufer, A. “Mercury and other iron-rich planetary bodies as relics of inefficient accretion”, *Nature Geosci.* 7, 2014. [5] Jackson, A.P., Gabriel, T.S.J. & Asphaug, E. “Constraints on the pre-impact orbits of Solar System giant impactors”, *MNRAS* 474, 2017. [6] Cambioni, S. *et al.* “Realistic On-The-Fly Outcomes of Planetary Collisions: Machine Learning Applied to Simulations of Giant Impacts”, *Ap.J.* 875, 2019. [7] Emsenhuber, A. & Asphaug, E. “Fate of the runner in hit and run collisions”, *Ap.J.* 875, 2019.